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(54) Title: PLATING APPARATUS AND METHOD (57) Abstract <p>An apparatus for plating a conductive film directly on a substrate with a barrier layer on top includes anode rod (1) placed in tube (109), and anode rings (2, and 3) placed between cylindrical walls (107, 105), (103, 101) respectively. Anodes (1, 2, 3) are powered by power supplies (13, 12 and 11), respectively. Electrolyte (34) is pumped by pump (33) to pass through filter (32) and reach inlets of liquid mass flow controllers (LMFCs) (21, 22, 23). Then LMFCs (21, 22, 23) deliver electrolyte at a set flow rate to sub-plating baths containing anodes (3, 2, 1), respectively. After flowing through the gap between wafer (31) and the top of the cylindrical walls (101, 103, 105, 107 and 109), electrolyte flows back to tank (36) through spaces between cylindrical walls (100, 101), (103, 105), (107, 109), respectively. A pressure leak valve (38) is placed between the outlet of pump (33) and electrolyte tank (36) to leak electrolyte back to tank (36) when LMFCs (21, 22, 23) are closed. A wafer (31) held by wafer chuck (29) is connected to power supplies (11, 12 and 13). A drive mechanism (30) is used to rotate wafer (31) around the z axis, and oscillate the wafer in the x, y, and z directions shown. Filter (32) filters particles larger than 0.1 or 0.2 μm in order to obtain a low particle added plating process.</p>		

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PLATING APPARATUS AND METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

5

BACKGROUND OF THE INVENTION1. Field of the Invention:

The present invention relates generally to a method and apparatus for plating thin
10 films and, more particularly, plating metal films to form interconnects in semiconductor
devices.

2. Description of the Prior Art:

As semiconductor device features continue to shrink according to Moore's law,
interconnect delay is larger than device gate delay for 0.18 μm generation devices if
15 aluminum (Al) and SiO₂ are still being used. In order to reduce the interconnect delay,
copper and low k dielectric are a possible solution. Copper/low k interconnects provide
several advantages over traditional Al/SiO₂ approaches, including the ability to
significantly reduce the interconnect delay, while also reducing the number of levels of
metal required, minimizing power dissipation and reducing manufacturing costs. Copper
20 offers improved reliability in that its resistance to electromigration is much better than
aluminum. A variety of techniques have been developed to deposit copper, ranging from
traditional physical vapor deposition (PVD) and chemical vapor deposition (CVD)
techniques to new electroplating methods. *PVD Cu* deposition typically has a cusping
problem which results in voids when filling small gaps (<0.18 μm) with a large aspect
25 ratio. *CVD Cu* has high impurity incorporated inside the film during deposition, which
needs a high temperature annealing to drive out the impurity in order to obtain a low
resistivity Cu film. Only *electroplated Cu* can provide both low resistivity and excellent
gap filling capability at the same time. Another important factor is the cost; the cost of
electroplating tools is two thirds or half of that of *PVD* or *CVD tools*, respectively. Also,
30 low process temperatures (30° to 60°C) for electroplating Cu are advantageous with low
k dielectrics (polymer, xerogels and aerogels) in succeeding generations of devices.

Electroplated Cu has been used in printed circuit boards, bump plating in chip packages and magnetic heads for many years. In conventional plating machines, density of plating current flow to the periphery of wafers is greater than that to the center of wafers. This causes a higher plating rate at the periphery than at the center of wafers.

5 U.S. Pat. No. 4,304,841 to Grandia et al. discloses a diffuser being put between a substrate and an anode in order to obtain uniform plating current flow and electrolyte flow to the substrate. U.S. Pat. No. 5,443,707 to Mori discloses manipulating plating current by shrinking the size of the anode. U.S. Pat. No. 5,421,987 to Tzanavaras discloses a rotating anode with multiple jet nozzles to obtain a uniform and high plating

10 rate. U.S. Pat. No. 5,670,034 to Lowery discloses a transversely reciprocating anode in front of a rotating wafer to improve plating thickness uniformity. U.S. Pat. No. 5,820,581 to Ang discloses a thief ring powered by a separate power supply to manipulate the plating current distribution across the wafer.

All of these prior art approaches need a Cu seed layer prior to the Cu plating.

15 Usually the Cu seed layer is on the top of a diffusion barrier. This Cu seed layer is deposited either by physical vapor deposition (PVD), or chemical vapor deposition (CVD). As mentioned before, however, PVD Cu typically has a cusping problem, which results in voids when filling small gaps ($<0.18\text{ }\mu\text{m}$) with a large aspect ratio with subsequent Cu electroplating. CVD Cu has high impurity levels incorporated in the film

20 during deposition, requiring a high temperature annealing to drive out the impurities in order to obtain a low resistivity Cu seed layer. As device feature size shrinks this Cu seed layer will become a more serious problem. Also, deposition of a Cu seed layer adds an additional process, which increases IC fabrication cost.

Another disadvantage of the prior art is that the plating current and electrolyte

25 flow pattern are manipulated dependently, or only the plating current is manipulated. This limits the process tuning window, because the optimum plating current condition does not necessarily synchronize with optimum electrolyte flow condition for obtaining excellent gap filling capability, thickness uniformity and electrical uniformity as well as grain size and structure uniformity all at the same time.

30 Another disadvantage of the prior art is that plating head or plating systems are bulky with large foot prints, which causes higher cost of ownership for users.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a novel method and apparatus for plating a metal film directly on a barrier layer without using a seed layer produced by a process other than plating.

It is a further object of the invention to provide a novel method and apparatus for plating a metal film over a thinner seed layer than employed in the prior art.

It is an additional object of the invention to provide a novel method and apparatus for plating a thin film with a more uniform thickness across a wafer.

It is a further object of the invention to provide a novel method and apparatus for plating a conducting film with a more uniform electrical conductivity across a wafer.

It is a further object of the invention to provide a novel method and apparatus for plating a thin film with a more uniform film structure, grain size, texture and orientation.

It is a further object of the invention to provide a novel method and apparatus for plating a thin film with an improved gap filling capability across a wafer.

It is a further object of the invention to provide a novel method and apparatus for plating a metal film for interconnects in an integrated circuit IC chip.

It is a further object of the invention to provide a novel method and apparatus for plating a thin film, with the method and apparatus having independent plating current control and electrolyte flow pattern control.

It is a further object of the invention to provide a novel method and apparatus for plating a metal thin film for a damascene process.

It is a further object of the invention to provide a novel method and apparatus for plating a metal film with a low impurity level.

It is a further object of the invention to provide a novel method and apparatus for plating copper with a low stress and good adhesion.

It is a further object of the invention to provide a novel method and apparatus for plating a metal film with a low added particle density.

It is a further object of the invention to provide a novel plating system with a small footprint.

It is a further object of the invention to provide a novel plating system with a low cost of ownership.

It is a further object of the invention to provide a novel plating system which plates a single wafer at a time.

It is a further object of the invention to provide a novel plating system with an in-situ film thickness uniformity monitor.

It is a further object of the invention to provide a novel plating system with a built-in cleaning system with wafer dry-in and dry-out.

5 It is a further object of the invention to provide a novel plating system with a high wafer throughput.

It is a further object of the invention to provide a novel plating system which can handle a wafer size beyond 300 mm.

10 It is a further object of the invention to provide a novel plating system with multiple plating baths and cleaning/drying chambers.

It is a further object of the invention to provide a novel plating system with a stacked plating chamber and cleaning/dry chamber structure.

15 It is a further object of the invention to provide a novel plating system with automation features of the Standard Mechanical Interface (SMIF), the Automated Guided Vehicle (AGV), and the SEMI Equipment Communication Standard/Generic Equipment Machine (SECS/GEM).

It is a further object of the invention to provide a novel plating system meeting Semiconductor Equipment and Materials International (SEMI) and European safety specifications.

20 It is a further object of the invention to provide a novel plating system with high productivity having a large mean time between failures (MTBF), small scheduled down time, and large equipment uptime.

25 It is a further object of the invention to provide a novel plating system controlled by a personal computer with a standard operating system, such as an IBM PC under a Windows NT environment.

It is a further object of the invention to provide a novel plating system with a graphical user interface, such as a touch screen.

30 These and related objects and advantages of the invention may be achieved through use of the novel method and apparatus herein disclosed. A method for plating a film to a desired thickness on a surface of a substrate in accordance with the invention includes plating the film to the desired thickness on a first portion of the substrate surface. The film is then plated to the desired thickness on at least a second portion of the substrate to give a continuous film at the desired thickness on the substrate. Additional portions of the substrate surface adjacent to and contacting the film already

plated on one or more of the previous portions are plated as necessary to give a continuous film over the entire surface of the substrate.

An apparatus for plating a film on a substrate in accordance with the invention includes a substrate holder for positioning the substrate for contact with a plating electrolyte. The apparatus has at least one anode for supplying plating current to the substrate and at least two flow controllers connected to supply electrolyte contacting the substrate. At least one control system is coupled to the at least one anode and the at least two flow controllers to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

In another aspect of the invention, an apparatus for plating a film on a substrate in accordance with the invention includes a substrate holder for positioning the substrate for contact with a plating electrolyte. The apparatus has at least two anodes for supplying plating current to the substrate and at least one flow controller connected to supply electrolyte contacting the substrate. At least one control system is coupled to the at least two anode and the at least one flow controller to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

In a further aspect of the invention, an apparatus for plating a film on a substrate in accordance with the invention includes a substrate holder for positioning the substrate for contact with a plating electrolyte. The apparatus has at least one anode for supplying plating current to the substrate and at least one flow controller connected to supply electrolyte contacting the substrate. The at least one flow controller comprises at least three cylindrical walls, a first of the cylindrical walls positioned under a center portion of the substrate extending upward closer to the substrate than a second one of the cylindrical walls positioned under a second portion of the substrate peripheral to the center portion. A drive mechanism is coupled to the substrate holder to drive the substrate holder up and down to control one or more portions of the substrate contacting the electrolyte. At least one control system is coupled to the at least one anode and the at least one flow controller to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

In yet another aspect of the invention, an apparatus for plating a film on a substrate in accordance with the invention includes a substrate holder for positioning the substrate for contact with a plating electrolyte. The apparatus has at least one anode for supplying plating current to the substrate and at least one flow controller connected to
5 supply electrolyte contacting the substrate. The at least one flow controller comprises at least three cylindrical walls movable upward toward the substrate and downward away from the substrate, to adjust a gap between the substrate and each of the cylindrical walls to control one or more portions of the substrate contacting the electrolyte. A drive mechanism is coupled to the substrate holder to drive the substrate holder up and down
10 to control one or more portions of the substrate contacting the electrolyte. At least one control system is coupled to the at least one anode and the at least one flow controller to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

15 In still another aspect of the invention, an apparatus for plating a film on a substrate, includes a substrate holder for positioning the substrate in a body of electrolyte. At least one movable jet anode supplies plating current and electrolyte to the substrate. The movable jet anode is movable in a direction parallel to the substrate surface. A flow controller controls electrolyte flowing through the movable jet anode.
20 At least one control system is coupled to the movable jet anode and the flow controller to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

In a still further aspect of the invention, an apparatus for plating a film on a
25 substrate includes a substrate holder for positioning the substrate above an electrolyte surface. A first drive mechanism is coupled to the substrate holder to move the substrate holder toward and away from the electrolyte surface to control a portion of a surface of the substrate contacting the electrolyte. A bath for the electrolyte has at least one anode mounted in the bath. A second drive mechanism is coupled to the bath to rotate the bath
30 around a vertical axis to form a substantially parabolic shape of the electrolyte surface. A control system is coupled to the first and second drive mechanisms and to the at least one anode to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

In yet another aspect of the invention, an apparatus for plating a film on a substrate includes a substrate holder for positioning the substrate above an electrolyte surface. A first drive mechanism is coupled to the substrate holder to move the substrate holder toward and away from the electrolyte surface to control a portion of a surface of the substrate contacting the electrolyte. A second drive mechanism is coupled to the substrate holder to rotate the substrate holder around an axis vertical to the surface of the substrate. A third drive mechanism is coupled to the substrate holder to tilt the substrate holder with respect to the electrolyte surface. A bath for the electrolyte has at least one anode mounted in the bath. A control system is coupled to the first, second and third drive mechanisms and to the at least one anode to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

In a still further aspect of the invention, a method for plating a film to a desired thickness on a surface of a substrate includes providing a plurality of stacked plating modules and a substrate transferring mechanism. A substrate is picked from a substrate holder with the substrate transferring mechanism. The substrate is loaded into a first one of stacked plating modules with the substrate transferring mechanism. A film is plated on the substrate in the first the one of the stacked plating modules. The substrate is returned to the substrate holder with the substrate transferring mechanism.

In another aspect of the invention, an automated tool for plating a film on a substrate includes at least two plating baths positioned in a stacked relationship, at least one substrate holder and a substrate transferring mechanism. A frame supports the plating baths, the substrate holder and the substrate transferring mechanism. A control system is coupled to the substrate transferring mechanism, substrate holder and the plating baths to continuously perform uniform film deposition on a plurality of the substrates.

Method 1: Portion of wafer surface is contacted with electrolyte (static anode)

The above and other objects of the invention are further accomplished by a method for plating a thin film directly on substrate with a barrier layer on top, comprising: 1) flowing electrolyte on a portion of a substrate surface with a barrier layer
5 on the top; and 2) turning on DC or pulse power to plate metal film on the same portion area of substrate until the film thickness reaches the pre-set value; 3) repeating step 1 and 2 for additional portions of the substrate by flowing electrolyte to the same additional portion of substrate; 4) repeating step 3 until the entire substrate surface is plated with a thin seed layer; 5) flowing electrolyte to entire area of the substrate; 6) supplying power
10 to apply positive potential to all anodes to plate the thin film until the film thickness reaches a desired thickness value.

Method 2: Whole wafer surface is contacted by electrolyte (static anodes)

In a further aspect of the invention there is provided another method for plating a
15 thin film directly on a substrate with a barrier layer on top, comprising: 1) flowing electrolyte on the full surface of the substrate; 2) plating the thin film only on a portion of the substrate surface by applying positive potential on an anode close to the same portion of wafer surface and by applying negative potential on all other anodes close to the remainder of the substrate surface until the plated film thickness on the same portion
20 of the substrate reaches a pre-set value; 3) repeating step 2 for an additional portion of the substrate; 4) repeating step 3 until the whole area of substrate is plated with a thin seed layer; 5) plating a thin film on the whole area of the substrate at the same time by applying positive potential to all anodes until the thickness of the film on the whole surface of the substrate reaches a pre-set thickness value.

Method 3: Whole wafer surface is contacted by electrolyte at beginning, and then portion of wafer which has been plated is moved out of electrolyte

In a further aspect of the invention there is provided another method for plating a thin film directly on a substrate with a barrier layer on top, comprising: 1) flowing electrolyte on the full surface of a substrate; 2) plating the thin film only on a portion of the substrate surface by applying positive potential on an anode close to the same portion of the substrate surface and by applying negative potential on all other anodes close to the remainder of the substrate surface until the plated film thickness on the portion of the substrate surface reaches a pre-set value; 3) move the electrolyte only out of contact with the all plated portion of the substrate and keep the electrolyte still touching the rest of the non-plated portion of the substrate; 4) repeat steps 2 and 3 for plating the next portion of the substrate; 5) repeat step 4 until the whole area of the substrate is plated with a thin seed layer; 6) plate a thin film on the whole substrate at the same time by applying positive potential to all anodes and flowing electrolyte on the whole surface of the substrate until the thickness of the film on the whole surface of the substrate reaches a pre-set thickness value.

Method 4: A portion of substrate is contacted by electrolyte at beginning, and then both plated portion and the next portion of the substrate are contacted by electrolyte

In a further aspect of the invention there is provided another method for plating a thin film directly on a substrate with a barrier layer on top, comprising: 1) flowing electrolyte on a first portion of the substrate surface; and 2) plating the thin film only on the first portion of the substrate surface by applying positive potential on an anode close to the first portion of the substrate surface until the plated film thickness on the first portion of the substrate reaches a pre-set value; 3) moving the electrolyte to contact a second portion of the substrate surface and at the same time keep the electrolyte still contacting the first portion of the substrate surface; 4) plating the thin film only on the second portion of the substrate surface by applying positive potential on a anode close to the second portion of the substrate surface and applying a negative potential on an anode close to

electrolyte on the full surface of the substrate until the thickness of the film on the whole surface of the substrate reaches a pre-set thickness value.

5 Method 5: Portion of substrate surface is contacted with electrolyte (movable anodes) for seed layer plating only

10 In a further aspect of the invention there is provided another method for plating a thin film directly on a substrate with a barrier layer on top, comprising: 1) flowing electrolyte on a portion of the substrate surface with a barrier layer on the top through a movable jet anode; 2) turning on DC or pulse power to plate a metal film on the portion of the substrate until the film thickness reaches a pre-set value; 3) repeating steps 1 and 2 for an additional portion of the substrate by moving the movable jet anode close to the additional portion of the substrate; 4) repeating step 3 until the whole area of the substrate is plated with a thin seed layer.

15 Method 6: Whole substrate surface is contacted by electrolyte (movable anodes) for seed layer plating only

20 In a further aspect of the invention there is provided another method for plating a thin film directly on a substrate with a barrier layer on top, comprising: 1) immersing the full surface of a substrate into an electrolyte; 2) plating the thin film only on a first portion of the substrate surface by applying positive potential on a movable anode close to the first portion of the substrate surface; 3) repeating step 2 for additional portions of the substrate by moving the movable anode close to the additional portions of the substrate; 4) repeating step 3 until the whole area of the substrate is plated with a thin seed layer.

25

Apparatus 1: Multiple Liquid Flow Mass Controllers (LMFCs) and Multiple Power Supplies

In a further aspect of the invention there is provided an apparatus for plating a thin film directly on a substrate with a barrier layer on top, comprising: a substrate holder
5 for holding a substrate above an electrolyte surface; at least two anodes, with each anode being separated by an insulating cylindrical wall; a separate liquid mass flow controller for controlling electrolyte flowing through a space between the two cylindrical walls to touch a portion of the substrate; a separate power supply to create a potential between each anode and cathode or the substrate; the portion of the substrate surface will be
10 plated only when the liquid flow controller and power supply corresponding to the portion of the substrate is turned on at the same time.

Apparatus 2: One Common LMFC and Multiple Power Supplies

In a further aspect of the invention there is provided another apparatus for plating
15 a thin film directly on a substrate with a barrier layer on top, comprising: a substrate chuck holding the substrate above an electrolyte surface; a motor driving the substrate holder up or down to control the portion of the surface area contacting the electrolyte; at least two anodes, with each anode being separated by two insulating cylindrical walls, the height of the cylindrical walls being reduced along the outward radial direction of the
20 substrate; one common liquid mass flow controller for controlling electrolyte flowing through spaces between each adjacent cylindrical wall to reach the substrate surface; separate power supplies to create potential between each anode and cathode or the substrate; a portion of the substrate surface is plated only when the anode close to the portion of the substrate is powered to positive potential and the rest of anodes are
25 powered to negative potential and the portion of the substrate is contacted by the electrolyte at the same time. After the plating thickness reaches a seed layer set-value, the substrate is moved up so that the plated portion is out of the electrolyte. This will allow no further plating or etching when other portions of the substrate are plated.

Apparatus 3: Multiple LMFCs and One Common Power Supply

In a further aspect of the invention there is provided another apparatus for plating a thin film directly on a substrate with a barrier layer on top, comprising: a substrate holder holding the substrate above an electrolyte surface; at least two anodes, each anode
5 being separated by two insulating cylindrical walls; a separate liquid mass flow controller for controlling electrolyte flowing through a space between the two cylindrical walls to touch a portion of the substrate; one common power supply to create potential between each anode and cathode or the substrate; a portion of the substrate surface is plated only when its liquid mass flow controller and the power supply are turned on at
10 the same time.

Apparatus 4: One Common LMFC and One Common Power Supply

In a further aspect of the invention there is provided another apparatus for plating a thin film directly on a substrate with a barrier layer on top, comprising: a substrate
15 holder holding the substrate above an electrolyte surface; at least two anodes, each anode being separated by two insulating cylindrical walls; the cylindrical walls can be moved up and down to adjust a gap between the substrate and the top of the cylindrical walls, thereby to control electrolyte to contact a portion of the substrate adjacent to the walls, one liquid mass flow controller for controlling electrolyte flowing through a space
20 between the two cylindrical walls; one power supply to create potential between all anodes and a cathode or the substrate; a portion of the substrate surface will be plated only when the cylindrical wall below the portion of the substrate surface is moved up so that the electrolyte touches the portion of the substrate and the power supply is turned on at the same time.

25

Apparatus 5: Movable Anode with Substrate not Immersed in Electrolyte

only when the portion of the surface is contacted by electrolyte ejected from the movable anode jet.

Apparatus 6: Movable Anode with Substrate Immersed in Electrolyte

5 In a further aspect of the invention there is provided another apparatus for plating a thin film directly on a substrate with a barrier layer on top, comprising: a substrate holder for holding a substrate, with the substrate being immersed in electrolyte; a movable anode jet adjacent to the substrate, the movable anode jet being movable toward the substrate surface, whereby the plating current from the anode jet can be
10 controlled to go to any portion of the substrate; one power supply to create potential between the movable anode jet and a cathode or the substrate; a portion of substrate surface is plated only when the portion of the substrate is close to the movable anode jet.

Method 7: Plating Metal Film on to Substrate through a Fully Automation Plating Tool

15 In a further aspect of the invention there is provided another method for plating a thin film onto a substrate through a fully automated plating tool, comprising: 1) picking up a wafer from a cassette and sending to one of stacked plating baths with a robot; 2) plating metal film on the wafer; 3) after finishing the plating, picking up the plated wafer from the stacked plating bath with the robot and transporting it to one of the stacked
20 cleaning/drying chambers; 4) Cleaning the plated wafer; 5) drying the plated wafer; 6) picking up the dried wafer from the stacked cleaning/drying chamber with the robot and transporting it to the cassette.

Apparatus 7: Fully Automated Tool for Plating Metal Film on to Substrate

25 In a further aspect of the invention there is provided a fully automated tool for plating a metal film onto a substrate, comprising: a robot transporting a wafer; wafer cassettes; multiple stacked plating baths; multiple stacked cleaning/drying baths; an electrolyte tank; and a plumbing box holding a control valve, filter, liquid mass flowing controller, and plumbing. The fully automated tool further comprises a computer and
30 control hardware coupled between the computer and the other elements of the automated tool, and an operating system control software package resident on the computer.

Method 8: Plating thin layer -- Portion of wafer surface is contacted with electrolyte, and then both plated portion and the next portion of wafer are contacted by electrolyte and are plated by metal

In a further aspect of the invention there is provided another method for plating a thin film directly on a substrate with a barrier layer or thin seed layer on top, comprising:

5 1) turning on DC or pulse power, 2) making a first portion of the substrate surface contact an electrolyte, so that a metal film is plated on the first portion of the substrate; 3) when the metal film thickness reaches a pre-set value, repeating step 1 and 2 for one or more additional portions of the substrate by making the one or more additional

10 portions of the substrate contact the electrolyte, while continuing to plate the first portion of the substrate and any previous of the one or more additional portions of the substrate; 4) repeating step 3 until the entire area of the substrate is plated with a thin seed layer.

Method 9: Plating thin layer then thick layer -- Portion of wafer surface is contacted with electrolyte, and then both plated portion and the next portion of wafer are contacted by electrolyte and are plated by metal

In a further aspect of the invention there is provided another method for plating a film directly on substrate with a barrier layer or thin seed layer on top, comprising: 1) turning on DC or pulse power, 2) making a first portion of a substrate surface contact an

20 electrolyte, so that a metal film is plated on the first portion of the substrate; 3) when the metal film thickness reaches a pre-set value, repeating step 1 and 2 for one or more additional portions of the substrate by making the one or more additional portions of the substrate contact the electrolyte, while continuing to plate the first portion of the substrate and any previous of the one or more additional portions of the substrate; 4)

25 repeating step 3 until all portions of the substrate are plated with a thin seed layer; 5) contacting all of the portions of the substrate with the electrolyte; 6) applying

applying a positive potential on a first anode close to a first portion of the substrate surface; 2) contacting the first portion of the substrate surface with the electrolyte, so that the film is plated on the first portion of the substrate surface; 3) when the film thickness on the first portion of the substrate surface reaches a pre-set value, further contacting a second portion of the substrate surface while maintaining electrolyte contact with the first portion of the substrate surface; 4) plating the film only on the second portion of the substrate surface by applying positive potential on a second anode close to the second portion of the substrate surface and applying a sufficient positive potential on the first anode close to the first portion of the substrate surface so that the first portion of the substrate surface is not plated but also not depleted; 5) repeating steps 3 and 4 for plating a third portion of the substrate while avoiding deplating of the first and second portions of the substrate surface; 6) repeating step 4 for successive areas of the substrate surface until whole area of the substrate surface is plated with a thin seed layer.

15 Method 11: Plating thin layer then thick layer -- A portion of wafer is contacted by electrolyte at beginning, and then both plated portion and the next portion of wafer are contacted by electrolyte, and only the next portion of wafer is plated

In a further aspect of the invention there is provided another method for plating a film directly on substrate with a barrier layer or thin seed layer on top, comprising: 1) contacting a first portion of a substrate area with an electrolyte; and 2) plating thin film only on the first portion of the substrate surface by applying positive potential on a first anode close to the same portion of wafer surface until a plated film thickness on the first portion of the substrate surface reaches a pre-set value; 3) further contacting a second portion of the substrate surface while maintaining electrolyte contact with the first portion of the substrate surface; 4) plating the film only on the second portion of the substrate surface by applying positive potential on a second anode close to the second portion of the substrate surface and applying a sufficient positive potential on the first anode close to the first portion of the substrate surface so that the first portion of the substrate surface is not plated but also not depleted; 5) repeating steps 3 and 4 for plating a third portion of the substrate while avoiding deplating of the first and second portions of the substrate surface; 6) repeating step 4

the substrate surface until a thickness of the further film on the whole substrate surface reaches a desired thickness value.

Apparatus 8: Rotating plating bath to form parabolic shape of electrolyte (single-anode)

5 In a further aspect of the invention there is provided another apparatus for plating a film directly on a substrate with a barrier layer or thin seed layer on top, comprising: a substrate chuck holding the substrate above an electrolyte surface; a motor driving the substrate holder up or down to control the portion of the surface area contacting the electrolyte; a bath with an anode immersed; a liquid mass flow controller for controlling
10 electrolyte flowing to contact the substrate; a power source to create potential between the anode and a cathode or substrate; another motor driving the plating bath to rotate around its central axis at such a speed that a surface of the electrolyte surface forms a parabolic shape; a portion of the substrate surface is plated only when the liquid mass flow controller and the power supply are turned on at the same time. After a plating
15 thickness reaches a seed layer predetermined value, the substrate is moved down so that the next portion of the substrate is contacting the electrolyte and is plated.

Apparatus 9: Rotating plating bath to form parabolic shape of electrolyte (multi-anodes)

In a further aspect of the invention there is provided another apparatus for plating
20 a film directly on a substrate with a barrier layer or thin seed layer on top, comprising: a substrate chuck holding the substrate above an electrolyte surface; a motor driving the substrate holder up or down to control the portion of the surface area contacting the electrolyte; at least two anodes, each anode being separated by two insulating cylindrical walls; a separate liquid mass flow controller for controlling electrolyte flowing through a
25 space between the two cylindrical walls to contact a portion of the substrate; separate power supplies to create potential between each anode and cathode or the substrate; another motor driving the plating bath to rotate around its central axis at such a speed that a surface of the electrolyte surface forms

Apparatus 10: Tilting wafer holder around y-axis or x-axis (single-anode)

In a further aspect of the invention there is provided another apparatus for plating a film directly on a substrate with a barrier layer or thin seed layer on top, comprising: a substrate chuck holding the substrate above an electrolyte surface, the substrate holder
5 being rotatable around a z-axis, and also tiltable around a y-axis or an x-axis; an anode; a liquid mass flow controller for controlling the electrolyte to contact the substrate; a power source to create potential between the anode and a cathode or substrate; a peripheral portion of the substrate surface will be plated only when the substrate chuck is tilted around the y-axis or x-axis and is rotated around the z-axis so that the peripheral
10 portion of the substrate is contacted by electrolyte, and the liquid mass flow controller and power source are turned on at the same time.

Apparatus 11: Tilting rotation axis of wafer holder (multi-anodes)

In a further aspect of the invention there is provided another apparatus for plating
15 a film directly on a substrate with a barrier layer or thin seed layer on top, comprising: a substrate chuck holding the substrate above an electrolyte surface, the substrate holder being rotatable around a z-axis, and also tiltable around a y-axis or an x-axis; at least two anodes, each anode being separated by two insulating cylindrical walls; a separate liquid mass flow controller for controlling electrolyte flowing through a space between the two
20 cylindrical walls to contact a portion of the substrate; separate power supplies to create potential between each anode and cathode or the substrate; a peripheral portion of the substrate surface will be plated only when the substrate chuck is tilted around the y-axis or x-axis and is rotated around the z-axis so that the peripheral portion of the substrate is contacted by electrolyte, and the liquid mass flow controllers and power source are
25 turned on at the same time.

Apparatus 12:

to contact the substrate; a power source to create potential between the anode and a cathode or substrate; another motor driving the plating bath to rotate around its central axis at such a speed that a surface of the electrolyte surface forms a parabolic shape; a peripheral portion of the substrate surface will be plated only when the substrate chuck is
5 tilted around the y-axis or x-axis and is rotated around the z-axis so that the peripheral portion of the substrate is contacted by electrolyte, and the liquid mass flow controller and power source are turned on at the same time.

10 Apparatus 13: Rotating plating bath to form parabolic shape of electrolyte and tilting wafer holder around y-axis or x-axis (multi-anodes)

In a further aspect of the invention there is provided another apparatus for plating a film directly on a substrate with a barrier layer or thin seed layer on top, comprising: a substrate chuck holding the substrate above an electrolyte surface; a motor driving the substrate holder up or down to control the portion of the surface area contacting the
15 electrolyte; the substrate holder being rotatable around a z-axis, and also tiltable around a y-axis or an x-axis; at least two anodes, each anode being separated by two insulating cylindrical walls, the cylindrical walls being closer to the substrate at its center than at its edge; a separate liquid mass flow controller for controlling electrolyte flowing through a space between the two cylindrical walls to contact a portion of the substrate; separate
20 power supplies to create potential between each anode and cathode or the substrate; another motor driving the plating bath to rotate around its central axis at such a speed that a surface of the electrolyte surface forms a parabolic shape; a portion of the substrate surface will be plated only when the anode close to that portion of the substrate is powered to positive as well as that portion of the substrate surface being contacted by
25 electrolyte at the same time. After a plating thickness reaches a predetermined value, the substrate is moved down so that the next portion of the substrate is contacted by the electrolyte and is plated.

The central idea of this invention for plating a metal film without using a seed
30 layer produced by a process other than plating is to plate one portion of wafer a time to reduce current load to a barrier layer, since the barrier layer typically has 100 times higher resistivity than a copper metal film. For details, please see following theoretical analysis.

The attainment of the foregoing and related objects, advantages and features of the invention should be more readily apparent to those skilled in the art, after review of the following more detailed description of the invention, taken together with the drawings, in which:

5

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A is a portion of a prior art plating apparatus, useful for understanding the invention.

Figure 1B is a plan view of a substrate shown in Figure 1.

10 Figure 2 is a corresponding plan view of a substrate during plating in accordance with the invention.

Figure 3A is a plan view of a portion of a plating apparatus in accordance with the invention.

15 Figure 3B is a view, partly in cross section, taken along the line 3B--3B in Figure 3A, and partly in block diagram form, of a plating apparatus in accordance with the invention.

Figure 4A is a plan view of a substrate ready for plating in accordance with the invention.

20 Figure 4B is a cross section view, taken along the line 4A--4A of the substrate in Figure 4A.

Figure 5 is a set of waveform diagrams, useful for understanding operation of the Figures 3A-3B embodiment of the invention.

Figures 6A and 6B are partial cross section views of plated substrates, useful for further understanding of the invention.

25 Figures 7 and 8 are additional sets of waveform diagrams, useful for a further understanding operation of the Figures 3A-3B embodiment of the invention.

Figures 9A-9D are plan views of portions of alternative embodiments of plating apparatuses in accordance with the invention.

30 Figure 10 is a plot of waveforms obtained in operation of apparatus in accordance with the invention.

Figure 11 is a flow diagram for a process in accordance with the invention.

Figure 12 is a set of waveform diagrams for an another embodiment of a process in accordance with the invention.

Figure 13A is a plan view of a portion of a second embodiment of a plating apparatus in accordance with the invention.

Figure 13B is a view, partly in cross section, taken along the line 13B--13B in Figure 13A, and partly in block diagram form, of the second embodiment of a plating apparatus in accordance with the invention.

Figure 14A is a plan view of a portion of a third embodiment of a plating apparatus in accordance with the invention.

Figure 14B is a view, partly in cross section, taken along the line 14B--14B in Figure 14A, and partly in block diagram form, of the third embodiment of a plating apparatus in accordance with the invention.

Figure 15A is a plan view of a portion of a fourth embodiment of a plating apparatus in accordance with the invention.

Figure 15B is a view, partly in cross section, taken along the line 15B--15B in Figure 15A, and partly in block diagram form, of the fourth embodiment of a plating apparatus in accordance with the invention.

Figure 16A is a plan view of a portion of a fifth embodiment of a plating apparatus in accordance with the invention.

Figure 16B is a view, partly in cross section, taken along the line 16B--16B in Figure 16A, and partly in block diagram form, of the fifth embodiment of a plating apparatus in accordance with the invention.

Figure 17 is a cross section view of a portion of a fifth embodiment of a plating apparatus in accordance with the invention.

Figure 18A is a plan view of a portion of a sixth embodiment of a plating apparatus in accordance with the invention.

Figure 18B is a view, partly in cross section, taken along the line 18B--18B in Figure 18A, and partly in block diagram form, of the sixth embodiment of a plating apparatus in accordance with the invention.

Figure 19A is a plan view of a portion of a seventh embodiment of a plating apparatus in accordance with the invention.

Figure 19B is a view, partly in cross section, taken along the line 19B--19B in Figure 19A, and partly in block diagram form, of the seventh embodiment of a plating apparatus in accordance with the invention.

Figures 20A and 20B are views, partly in cross section and partly in block diagram form, of an eighth embodiment of a plating apparatus in accordance with the invention.

Figures 21A and 21B are views, partly in cross section and partly in block
5 diagram form, of a ninth embodiment of a plating apparatus in accordance with the invention.

Figure 22A is a plan view of a portion of a tenth embodiment of a plating apparatus in accordance with the invention.

Figure 22B is a view, partly in cross section, taken along the line 22B--22B in
10 Figure 22A, and partly in block diagram form, of the tenth embodiment of a plating apparatus in accordance with the invention.

Figures 23A and 23B are plan views of a portion of eleventh and twelfth embodiments of plating apparatus in accordance with the invention.

Figure 24A is a plan view of a portion of a thirteenth embodiment of a plating
15 apparatus in accordance with the invention.

Figure 24B is a view, partly in cross section, taken along the line 24B--24B in Figure 24A, and partly in block diagram form, of the thirteenth embodiment of a plating apparatus in accordance with the invention.

Figures 25A-25C are plan views of a portion of fourteenth, fifteenth and
20 sixteenth embodiments of plating apparatus in accordance with the invention.

Figure 31A is a plan view of a portion of a twenty fourth embodiment of a plating apparatus in accordance with the invention.

Figure 31B is a view, partly in cross section, taken along the line 31B--31B in Figure 31A, and partly in block diagram form, of the twenty fourth embodiment of a plating apparatus in accordance with the invention.

Figure 32A is a plan view of a portion of a twenty fifth embodiment of a plating apparatus in accordance with the invention.

Figure 32B is a view, partly in cross section, taken along the line 32B--32B in Figure 32A, and partly in block diagram form, of the twenty fifth embodiment of a plating apparatus in accordance with the invention.

Figure 33A is a plan view of a portion of a twenty sixth embodiment of a plating apparatus in accordance with the invention.

Figure 33B is a view, partly in cross section, taken along the line 33B--33B in Figure 33A, and partly in block diagram form, of the twenty sixth embodiment of a plating apparatus in accordance with the invention.

Figures 34A-34D are cross section views of a portion of twentieth seventh through thirtieth embodiments of plating apparatus in accordance with the invention.

Figure 35 shows a substrate during plating with a process in accordance with the invention.

Figures 36A-36D are plan

Figure 40B is a view, partly in cross section, taken along the line 40B--40B in Figure 40A, and partly in block diagram form, of the thirty eighth embodiment of a plating apparatus in accordance with the invention.

Figure 41A is a plan view of a portion of a thirty ninth embodiment of a plating
5 apparatus in accordance with the invention.

Figure 41B is a view, partly in cross section, taken along the line 41B--41B in Figure 41A, and partly in block diagram form, of the thirty ninth embodiment of a plating apparatus in accordance with the invention.

Figure 42A is a plan view of a portion of a fortieth embodiment of a plating
10 apparatus in accordance with the invention.

Figure 42B is a view, partly in cross section, taken along the line 42B--42B in Figure 42A, and partly in block diagram form, of the fortieth embodiment of a plating apparatus in accordance with the invention.

Figures 43 and 44 are sets of waveform diagrams useful for understanding
15 operation of the embodiment of Figures 42A and 42B.

Figure 45A is a plan view of a portion of a forty first embodiment of a plating apparatus in accordance with the invention.

Figure 45B is a view, partly in cross section, taken along the line 45B--45B in Figure 45A, and partly in block diagram form, of the forty first embodiment of a plating
20 apparatus in accordance with the invention.</

Figure 48B is a view, partly in cross section, taken along the line 48B--48B in Figure 48A, and partly in block diagram form, of the forty fourth embodiment of a plating apparatus in accordance with the invention.

Figure 49A is a plan view of a portion of a forty fifth embodiment of a plating
5 apparatus in accordance with the invention.

Figure 49B is a view, partly in cross section, taken along the line 49B--49B in Figure 49A, and partly in block diagram form, of the forty fifth embodiment of a plating apparatus in accordance with the invention.

Figure 50 is a view, partly in cross section and partly in block diagram form, of a
10 forty sixth embodiment of a plating apparatus in accordance with the invention.

Figure 51 is a view, partly in cross section and partly in block diagram form, of a forty seventh embodiment of a plating apparatus in accordance with the invention.

Figures 52A-52C are schematic top, cross section and side views of a first embodiment of a plating system in accordance with the invention.

Figure 53 is a flow diagram of operation of a portion of software for controlling
15 the plating system of Figure 52.

Figures 54A-54C are schematic top, cross section and side views of a second embodiment of a plating system in accordance with the invention.

Fig

Figure 61 is a partly cross section and partly schematic view of a fiftieth embodiment of a plating apparatus in accordance with the invention.

Figures 62-71 are schematic views of fifty first through sixtieth embodiments of plating apparatuses in accordance with the invention.

5

DETAILED DESCRIPTION OF THE INVENTION

Turning now to the drawings, more particularly to Figures 1A-1B, there is shown a portion of a prior art plating apparatus, useful for understanding the present invention.

10 Theoretical calculation of potential difference between center and edge of wafer during conventional plating

Figs. 1A shows a cross section view of a conventional fountain type plating tool and a semiconductor wafer 31 with a thin barrier layer 400. The following theoretical calculation is for determining the potential difference between the center and the periphery of the wafer during normal plating. Assuming plating current density on the whole wafer surface is the same, the potential difference can be calculated by the following formula:

$$20 \quad V = \left(\frac{I_0 \rho_s}{4\pi r_0^2} \right) (r^2 - r_0^2) \quad (1)$$

where: r is the radius (cm), r_0 is the radius of a wafer (cm), I_0 is the total plating current flow to the wafer (Amp.), ρ_s is the sheet resistance of barrier layer (Ω/square).

25 Assuming the atomic radius = 3 \AA , then we can calculate that the surface density is $1\text{E}15 \text{ atom}/\text{cm}^2$. The density of current flowing to the wafer can be expressed as:

$$30 \quad I_D = \left(\frac{2 \times 1\text{E}15}{60} \right) \left(\frac{q \text{ P.R.}}{D_{\text{atom}}} \right) \quad (2)$$

where, I_D is the plating current density (A/cm^2), q is the charge of an electron (C), P.R. is the plating rate ($\text{\AA}/\text{min}$), D_{atom} is the diameter of an atom. Substitute P.R. = 2000 $\text{\AA}/\text{min}$, $q = 1.82E-19$ C, and $= 3 \text{\AA}$ into eq.(2):

5

$$I_D = \left(\frac{2 \times 1E15}{60} \right) \left(\frac{1.62E-19 \times 2000}{3} \right) = 3.6 E-3 A/cm^2 \quad (3)$$

10 Total current flowing to a 200 mm wafer is

$$I_0 = \pi r_0^2 I_D = 3.14 \times 100 \times 3.6E-3 = 1.13 \text{ Amp.} \quad (4)$$

Sheet resistance depends on thickness of film, and the method of depositing the film.

15 Sheet resistance at thickness of 200 \AA and deposited by a normal PVD or CVD method is in a range of 100 to 300 Ω/square . Substituting above $I_0 = 1.13$ Amp., $\rho_s = 100$ to 300 Ω/square , and $r = 0$, $r_0 = 10$ cm into eq.(1), the potential difference between the center and the periphery (edge) of the wafer is:

20 $V = 8.96 \text{ to } 26.9 \text{ Volt.} \quad (5)$

The normal plating voltage in acid Cu plating is in a range of 2 to 4 Volts. It is clear that such a potential difference will make it impossible to plate directly onto barrier layer by a conventional plating tool. Even though metal still can be plated on the center
25 of the wafer by using over voltage, a substantial quantity of H^+ ions will come out together with metal ions at the periphery of the wafer, which makes a poor quality of metal film. For the semiconductor interconnect application, plated copper film will have a very large resistivity, and poor morphology.

30 Theoretical calculation of potential difference between outside and inside of plating area during plating of the invention

As shown in Fig. 2, the invention only plates a portion of wafer at one time. The potential difference between the position at radius r_2 and the position at radius r_1 can be expressed as:

$$\begin{aligned}
 V_{21} &= \int dv = \int I dR = \int I_D (\pi r_2^2 - \pi r_1^2) (\rho_s / 2\pi r) dr \\
 &= (I_D \rho_s / 2) [(0.5 r_2^2 - r_1^2 \ln r_2) - (0.5 r_1^2 - r_1^2 \ln r_1)] \quad (6)
 \end{aligned}$$

The worst case is on the periphery of the wafer. Substitute $r_1 = 9$ cm, $r_2 = 10$ cm, $I_D = 3.6E-3$ Amp. (corresponding to P.R. = 2000 Å /min), $\rho_s = 100$ to 300 Ω/square into eq.(6):

$$V_{21} = 0.173 \text{ to } 0.522 \text{ Volts} \quad (7)$$

Hydrogen overvoltage is about 0.83 V. It is clear that no hydrogen comes out during plating in accordance with the invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

In describing the variety of embodiments of the invention, corresponding parts in different figures are designated with the same reference number in order to minimize repetitive description.

1. Multiple power supplies and multiple LMFCs

Figs. 3A-3B are schematic views of one embodiment of the apparatus for plating a conductive film directly on a substrate with a barrier layer on top in accordance with the present invention. The plating bath includes anode rod 1 placed in tube 109, and anode rings 2, and 3 placed between cylindrical walls 107 and 105, 103 and 101, respectively. Anodes 1, 2, and 3 are powered by power supplies 13, 12, and 11, respectively. Electrolyte 34 is pumped by pump 33 to pass through filter 32 and reach inlets of liquid mass flow controllers (LMFCs) 21, 22, and 23. Then LMFCs 21, 22 and 23 deliver electrolyte at a set flow rate to sub-plating baths containing anodes 3, 2 and 1,

respectively. After flowing through the gap between wafer 31 and the top of the cylindrical walls 101, 103, 105, 107 and 109, electrolyte flows back to tank 36 through spaces between cylindrical walls 100 and 101, 103 and 105, and 107 and 109, respectively. A pressure leak valve 38 is placed between the outlet of pump 33 and electrolyte tank 36 to leak electrolyte back to tank 36 when LMFCs 21, 22, 23 are closed. Bath temperature is controlled by heater 42, temperature sensor 40, and heater controller 44. A wafer 31 held by wafer chuck 29 is connected to power supplies 11, 12 and 13. A drive mechanism 30 is used to rotate wafer 31 around the z axis, and oscillate the wafer in the x, y, and z directions shown. The LMFCs are anti-acid or anti corrosion, and contamination free type mass flow controllers of a type known in the art. Filter 32 filters particles larger than 0.1 or 0.2 μm in order to obtain a low particle added plating process. Pump 33 should be an anti-acid or anticorrosion, and contamination free pump. Cylindrical walls 100, 1001, 103, 105, 107 and 109 are made of electrically insulating, anti-acid or anti-corrosion, and non-acid dissolved, metal free materials, such as tetrafluoroethylene, polyvinyl chloride (PVC), polyvinylidene fluoride (PVDF), polypropylene, or the like.

Figs. 4A-4B show the wafer 31 with barrier layer 203 on top. The barrier layer 203 is used to block diffusion of the plated metal into the silicon wafer. Typically, titanium nitride or tantalum nitride are used. In order to reduce the contact resistance between the cathode lead wire and the barrier layer, a metal film 201 is deposited by PVD or CVD on the periphery of wafer 31. The thickness of metal film 201 is in a range of 500 \AA to

During the above plating process, the power supplies can be operated in DC mode, pulse mode, or DC pulse mixed mode. In DC mode, the power supplies can be operated in a constant current mode, or a constant voltage mode, or a combination of the constant current mode and constant voltage mode. The combination of the constant
5 current mode and constant voltage mode means that the power supply can be switched from one mode to the other mode during the plating process. Fig 5 shows each power on/off sequence during a representative seed layer plating. T_p is called plating time, i.e. positive pulse on time during one cycle; T_e is called etching time, i.e. negative pulse on time during one cycle. T_e/T_p is called the etching plating ratio. It is generally in the range
10 of 0 to 1. As shown in Fig. 6A and 6B, a large ratio of T_e/T_p means better gap filling or less cusping, but a lower plating rate. A small ratio of T_e/T_p means a higher plating rate, but poor gap filling or more cusping.

1B. Process steps for succeeding metal plating on the metal seed layer plated in process

15 1A.

Step 6: Turn on LMFCs 21, 22, and 23. In principle, the flow rate of electrolyte from each LMFC is set as proportional to wafer area covered by the corresponding anode.

Step 7: After all flow is stabilized, turn on power supplies 11, 12, and 13. In principle, the current of each power supply is also set as proportional to the wafer area covered by
20 corresponding anode.

As shown in Fig. 8, instead of using the bipolar pulse wave form (a), a modified sine-wave pulse wave form (b), a unipolar pulse wave form (c), a pulse reverse wave form (d), a pulse-on-pulse wave form (e), or a duplex pulse wave form (f) can be used.

In a seed layer plating process, a sequence of anode 3, then anode 2, and then anode 1 is usually preferred, but the plating sequence can also be as follows:

- 1) anode 1, then anode 2, and then anode 3;
- 2) anode 2, then anode 1, and then anode 3;
- 3) anode 2, then anode 3, and then anode 1;
- 4) anode 3, then anode 1, and then anode 2; or
- 5) anode 1, then anode 3, and then anode 2

Figs. 9A-9D show schematic cross section views of other embodiments of anode and wall shapes. It can be seen that the wafer area above the space between electrode 103 and 105 receives less plating current than the wafer area above anode 3 does in the case of Fig. 3. This causes thickness variation across the wafer if wafer is only rotated during plating process. In order to plate a better uniformity of film without oscillating wafer in the x and y directions, the shape of the anodes and walls can be, for example, a triangle, square, rectangle, pentagon, polygon, or ellipse. In these ways, the plating current distribution can be averaged out across the wafer.

Fig. 10 shows a mechanism to verify if the seed layer becomes a continuous film across the whole wafer. Since the resistivity of a barrier layer (Ti/TiN

if V_{12} and V_{13} are close to each other, then the film on the wafer area above anode 1 is continuous;

if V_{12} and V_{13} are significantly different, then the film on the wafer area above anode 1 is not continuous;

5 3) if V_{11} , V_{12} and V_{13} are large, then at least the film on the wafer area above anode 3 is not continuous;

 further under condition (3)

if V_{12} and V_{13} are significantly different, then the film on the wafer areas above anode 2 and anode 1 are not continuous;

10 If V_{11} and V_{12} are significantly different, and V_{12} and V_{13} are close to each other, then the film on the wafer area above anode 2 is not continuous, but the film on the wafer area above area 1 is continuous;

 If V_{11} and V_{12} are close to each other, and V_{12} and V_{13} are significantly different, then the film on the wafer area anode 2 is continuous, and the film on the wafer
15

$$\begin{aligned} & \text{F.R. 2} \times f(\text{valve 52}) + \\ & \text{F.R. 1} \times f(\text{valve 53}) \end{aligned}$$

where: F.R. 1 is the flow rate setting for anode 1, F.R. 2 the flow rate setting for anode 2,
 5 and F.R. 3 is the flow rate setting for anode 3, and $f(\text{valve \#})$ is the valve status function defined as follows:

$$\begin{aligned} f(\text{valve \#}) = & \quad 1, \text{ when valve \# is turned on;} \\ & \quad 0, \text{ when valve \# is turned off.} \end{aligned}$$

Figs. 14A-14B show another embodiment of apparatus for plating a conductive
 10 film in accordance with the present invention. The embodiment of Figs. 14A-14B is similar to that of Figs. 3A-3B except that LMFCs 21, 22 and 23 are replaced by on/off valves 51, 52, 53 and three pumps 33. Electrolyte flowing to each anode is controlled independently by one pump 33 and one on/off valve.

Figs. 15A-15B show another embodiment of apparatus for plating a conductive
 15 film in accordance with the present invention. The embodiment of Figs. 15A-15B is similar to that of Figs. 3A-3B except that additional anodes 5 and 4 are added between cylindrical

Step 6: Repeat step 4 for anode 1 (turn on LMFC 24, valves 81, 82, 83, and power supply 14, and turn off LMFCS 21, 22, 23, valve 84, and power supplies 11, 12, 13).

In the above seed layer plating process, instead of plating from the periphery of the wafer to the center of the wafer, the plating also can be performed from the center to the periphery, or can be performed with a randomly chosen anode sequence.

2B. Process steps for succeeding metal plating on the metal seed layer plated in process

2A.

Step 7: Turn on LMFCS 21, 22, 23 and 24 and turn off valves 81, 82, 83, 84. In principle, the flow rate of electrolyte from each LMFC is set as proportional to the wafer area covered by the corresponding anode.

Step 8: After all flow is stabilized, turn on power supplies 11, 12, 13 and 14. In principle, the current of each power supply is set as proportional to the wafer area covered by the corresponding anode.

Step 9: Turn off power supplies 11, 12, 13 and 14 at the same time when plating current is used as thickness uniformity tuning variable. The power supplies can also be turned off at different times for adjusting plating film thickness uniformity.

Figs. 16A-16B

Step 4: Turn on LMFC 22 only, turn off LMFCS 21, 23, 24. In this way, even whole wafer area is immersed in the electrolyte, only the wafer area above anode 3 is facing the flowing electrolyte from LMFC 22.

Step 5: Repeat step 2 to 3 for anode 3 (turn on power supply 12 to output positive potential to anode 3, and power supplies 11, 13, and 14 to output negative potential to anode 4, 2, and 1, and turn off LMFCS 21, 23, 24).

Step 6: Repeat step 4 to 5 for anode 2 (turn on LMFC 23, and power supply 13 to output positive potential to anode 2, and power supplies 11, 12, and 14 to output negative potential to anode 4, 3, and 1, and turn off LMFCS 21, 22, 24).

Step 7: Repeat step 4 to 5 for anode 1 (turn on LMFC 24, and power supply 14 to output positive potential to anode 1, and power supplies 11, 12, and 13 to output negative potential to anode 4, 3 and 2, and turn off LMFCS 21, 22, 23).

In the above seed layer plating process, instead of plating from the periphery of the wafer to the center of the wafer, the plating also can be performed from the center to the periphery, or can be performed with a randomly chosen anode sequence.

3B. Process steps for succeeding metal plating on the metal seed layer plated

4A. Process steps for plating conductive film (or seed layer) directly on barrier layer.

Step 1: Turn on LMFC 21 only and move cylindrical walls 101, 103 close to the wafer, so that electrolyte only touches the portion of the wafer above cylindrical walls 101 and 103.

Step 2: After the flow of electrolyte is stabilized, turn on power supply 11. Positive metal ions will be plated onto the portion of wafer 31 above cylindrical walls 101 and 103.

Step 3: When the thickness of the conductive film reaches the predetermined set-value or thickness, turn off power supply 11, turn off LMFC 21, and move cylindrical walls 101 and 103 to a lower position.

Step 4: Repeat step 1 to 3 for cylindrical walls 105 and 107 (LMFC 22, cylindrical wall 105 and 107, and power supply 12).

Step 5: Repeat step 4 for tube 109 (LMFC 23, tube 109, and power supply 13).

4B. Process steps for succeeding metal plating on the metal seed layer plated in process 4A.

Step 6: Turn on LMFCs 21, 22, and 23, and move all cylindrical walls 101, 103, 105

Table 2

Combination type	Anode connection to power supply in each sector	Sector connection to LMFC
1	Each anode is connected to an independent power supply	Each sector is connected to an independent LMFC
2	Each anode is connected to an independent power supply	Sectors on the same radius are connected to an independent LMFC
3	Each anode is connected to an independent power supply	All sectors are connected to one common LMFC
4	Anodes on the same radius are connected to an independent power supply	Each sector is connected to an independent LMFC
5	Anodes on the same radius are connected to an independent power supply	Sectors on the same radius are connected to an independent LMFC
6	Anodes on the same radius are connected to an independent power supply	All sectors are connected to one common LMFC
7	All anodes are connected to one common power supply	Each sector is connected to an independent LMFC
8	All anodes are connected to one common power supply	Sectors on the same radius are connected to an independent LMFC
9	All anodes are connected to one common power supply	All sectors are connected to one common LMFC

5 In the above table, the operation of combination types 1, 2, 4, and 5 are the same as described above. In the case of combination types 1,2, and 3, the wafer rotating mechanism can be eliminated since each anode at a different sector is controlled by an independent power supply. For instance, the thickness of the plating film on a portion of

the substrate can be manipulated by controlling the plating current or the plating time of the anode below the same portion of the substrate. The operation of combination types 3, 6, 7, 8, 9 will be discussed later in detail.

5 Figs. 24A-24B show another embodiment of apparatus for plating a conductive film in accordance with the present invention. The embodiment of Figs. 24A-24B is similar to that of Figs. 3A-3B except that the cylindrical walls and anode ring are replaced by multiple rod type anodes 1 and tubes 109. Electrolyte comes out of the tubes 109, touches the wafer surface, and then flows back to the tank (not shown) through multiple holes 500. The tubes and anodes in a ring are placed in the same circle. There
10 are multiple holes between two adjacent ring of tubes and anodes for draining electrolyte back to tank 36. The following table 3 shows possible combinations of anode to power supply connection and each sector to LMFC.

Table 3

Combination type	Anode connection to power supply in each tube	Tube connection to LMFC
1	Each anode is connected to an independent power supply	Each tube is connected to an independent LMFC
2	Each anode is connected to an independent power supply	Tubes on the same radius are connected to an independent LMFC
3	Each anode is connected to an independent power supply	All tubes are connected to one common LMFC
4	Anodes on the same radius are connected to an independent power supply	Each tube is connected to an independent LMFC
5	Anodes on the same radius are connected to an independent power supply	Tubes on the same radius are connected to an independent LMFC
6	Anodes on the same radius are connected to an independent power supply	All tubes are connected to one common LMFC
7	All anodes are connected to one common power supply	Each tube is connected to an independent LMFC
8	All anodes are connected to one common power supply	Tubes on the same radius are connected to an independent LMFC
9	All anodes are connected to one common power supply	All tubes are connected to one common LMFC

5 In the above table, the operation of combination types 1, 2, 4, and 5 are the same as described above. In the case of combination types 1,2, and 3, the wafer rotating mechanism can be eliminated since each anode at a different tube is controlled by an independent power supply. For instance, the thickness of plating film on a portion of the

substrate can be manipulated by controlling the plating current or the plating time of the anode below the same portion of the substrate. The operation of combination types 3, 6, 7, 8, 9 will be discussed later in detail.

5 Instead of placing tubes and anodes on a circular ring, the tubes and anodes also can be placed on triangular, square, rectangular, pentagonal, polygonal, and elliptical rings. Triangular, square and elliptical rings are shown in Figs. 25A-25C.

2. Multiple LMFCs and Single Power Supply

10 Figs. 26A-26B show another embodiment of apparatus for plating a conductive film in accordance with the present invention. The embodiment of Figs. 26A-26B is similar to that of Figs. 3A-3B except that the anode rings and cylindrical walls are replaced by a single anode 240, bar 242 and valves 202, 204, 206, 208, 210, 212, 214, 216 and 218. The power supplies is reduced to a single power supply 200. The new valves are on/off valves, and are used to control electrolyte flowing to the wafer area.
15 Valves 208 and 212, 206 and 214, 204 and 216, 202 and 218 are placed symmetrically on bar 242, respectively.

5A. Process steps for plating conductive film (or seed layer) directly on barrier layer.

20 Step 1: Turn on pump 33, LMFC 55, and valves 202 and 218 as well as drive

5B. Process steps for succeeding metal plating on the metal seed layer plated in process
5A.

Step 8: Turn on LMFC 55 and all valves 202, 204, 206, 208, 210, 212, 214, 216, 218, so that electrolyte touches the whole wafer area.

5 Step 9: After all flow is stabilized, turn on power supplies 200.

Step 10: Turn off power supply 200 and all the valves when the film thickness reaches the set value. The valves can also be turned off at different times with the power supply 200 turned on for adjusting the plating film thickness uniformity within the wafer.

10 Fig. 27 shows another embodiment of apparatus for plating conductive film in accordance with the present invention. The embodiment of Fig. 27 is similar to that of Figs. 26A-26B, except that all valves are placed on the bar 242 with a different radius in order to plate metal with better uniformity. Plating process steps are described as follows:

15

6A. Process steps for plating conductive film (or seed layer) directly on barrier layer.

Step 1: Turn on pump

Step 9: After all flow is stabilized, turn on power supply 200.

Step 10: Turn off power supply 200 and all valves when the film thickness reaches the set value. The valves can also be turned off at different times with the power supply 200 turned on for adjusting plating film thickness uniformity within the wafer.

5 Fig. 28 shows another embodiment of apparatus for plating a conductive film in accordance with the present invention. The embodiment of Fig. 28 is similar to that of Fig. 26 except that an additional bar is added to form a cross shape bar structure 244. Valves 202 and 218, 204 and 216, 206 and 214, 208 and 212 are placed symmetrically on the horizontal portion of bar structure 244. Similarly, valves 220 and 236, 222 and 234, 224 and 232 are placed symmetrically on the vertical portion of the bar structure 244. All valves on the horizontal portion of bar 244 also have a different radius from those on the vertical portion of bar 244, respectively. Plating process steps are described as follows:

15 7A. Process steps for plating conductive film (or seed layer) directly on barrier layer.

Step 1: Turn on pump 33, LMFC 55, and valve 218 and 202 as well as drive 30, so that electrolyte coming out of valves 218 only touches the peripheral portion of the wafer above valves 218 and 202.

Step 8: Turn on LMFC 55 and all valves 202, 204, 206, 208, 210, 212, 214, 216, 218, 220, 222, 224, 232, 234, 236, so that electrolyte touches the whole wafer area.

Step 9: After all flow is stabilized, turn on power supply 200.

Step 10: Turn off power supply 200 and all valves when the film thickness reaches the set value. The valves can also be turned off at different times with the power supply 200 turned on for adjusting plating film thickness uniformity within the wafer.

Figs. 29A-29C show portions of an additional three embodiments of apparatus for plating a conductive film in accordance with the present invention. The embodiment of Fig. 29A is similar to that of Figs. 26A-26B except that the number of bars is increased to three. The angle between two adjacent bars is 60°. The embodiment of Fig. 29B is similar to that of Figs. 26A-26B except that the number of bars is increased to four. The angle between two adjacent bars is 45°. The embodiment of Fig. 29C is similar to that of Figs. 26A-26B except that the bar is reduced to 0.5, i.e. half a bar. Alternatively, the number of bars can be 5, 6, 7, or more.

The plating step sequence can be started from valves close to the periphery of the wafer, or started from the center of the wafer, or started randomly. Starting from the periphery of the wafer is preferred since the previously plated metal seed layer (

Step 2: After the flow of electrolyte is stabilized, turn on power supply 200. Positive metal ions will be plated onto the peripheral portion of wafer 31 above valves 356.

Step 3: When the thickness of the conductive film reaches the predetermined set-value or thickness, turn off power supply 200, LMFC 55, and valves 356.

5 Step 4: Move anode jet 254 to the next position with a smaller radius;

Step 5: Repeat step 1 to 4 until the whole wafer area is plated by the thin film.

The above process steps can be modified as follows:

Step1 : Same as above

Step2: Same as above

10 Step 3: When the thickness of the conductive film reaches a certain percentage of the predetermined set-value or thickness, start slowly moving anode jet 254 radially toward the wafer center. The rate of moving the anode jet 254 is determined by the predetermined set-value or thickness. Also since the surface area plated by the anode jet 254 is proportional to the radius of the position of anode jet 254, the rate of moving
15 anode jet 254 increases as it moves toward the wafer center.

Step

wafer 31 in order to focus plating current on a portion of wafer 31. The gap size is in a range of 0.1 mm to 5 mm, and preferably 1 mm. The process sequence is similar to that of Fig. 30.

Figs. 34A-34D show four embodiments of movable anodes in accordance with the present invention. Fig. 34A shows an anode structure consisting of anode 252 and case 262. Case 262 is made of insulator materials such as tetrafluoroethylene, PVC, PVDF, or polypropylene. Fig. 34B shows an anode structure consisting of anode 266 and case 264. The electrolyte is feed through a hole at the bottom of case 264. Fig. 34C shows an anode structure consisting of anode 262, electrodes 274 and 270, insulator spacer 272 and case 262, and power supplies 276, 268. Electrode 274 is connected to negative output of power supply 276, and electrode 270 is connected to cathode wafer 31. The function of electrode 274 is to trap any metal ions flowing out of case 262, therefore no film is plated on the wafer area outside of case 262. The function of electrode 270 is to prevent electrical field leakage from electrode 274 to minimize any etching effect. The embodiment of Fig. 34D is similar to that of Fig. 34C except that the case 264 has a hole at the bottom for electrolyte to flow through.

Fig. 35 shows the surface status of a wafer during plating. Wafer area 280 was plated by a seed layer, area 284 is in the process of plating, and wafer area 282 has not been plated.

Figs. 36A-36C show an additional three embodiments of apparatus for plating a conductive film in accordance with

and 37B are similar to that of Figs. 30A-30B, except that the wafer is placed upside down and vertically, respectively.

Figs. 38A-38B show another embodiment of apparatus for plating a conductive film in accordance with the present invention. The embodiment of Figs. 38A-38B is similar to that of Figs. 16A-16B except that all of the anodes are replaced by a one piece anode 8. Anode 8 is connected to single power supply 11. Plating process steps using this embodiment are described as follows:

9A. Process steps for plating conductive film (or seed layer) directly on barrier layer.

10 Step 1: Turn on LMFC 21 and valves 82,83, and 84 and turn off LMFCs 22, 23, 24 and valve 81, so that electrolyte only touches the portion of the wafer above sub-plating bath 66, and then flows back to tank 36 through the return paths of spaces between cylindrical walls 100 and 103, 105 and 107, 107 and 109, and tube 109.

15 Step 2: After the flow of electrolyte is stabilized, turn on power supply 11. Positive metal ions will be plated onto the portion of wafer 31 above sub-plating bath 66.

Step 3: When the thickness of the conductive film reaches the predetermined set-value or thickness, turn off power supply 11 and turn off LMFC 21.

Step 4: Repeat step

LMFCs can be turned off at different times in order to adjust the plating film thickness uniformity as shown in Fig. 39. At time t_1 , only LMFCs 21, 23, and 24 are turned off, and valves 81, 83, and 84 are also turned off. Therefore, electrolyte does not touch the wafer except in the area above sub-plating bath 64. As the power supply 11 remains turned on, metal ions will be plated only on the area above sub-plating bath 64. Then LMFC 22 turns off at time t_2 . Similarly, LMFC 24 turns on at time t_3 and turns off at time t_4 to obtain extra plating at the wafer area above sub-plating bath 60. Turn off time of t_2 and t_4 can be fine tuned by measuring wafer thickness uniformity.

Figs. 40A-40B show another embodiment of apparatus for plating a conductive film in accordance with the present invention. The embodiment of Figs. 40A-40B is similar to that of Figs. 3A-3B except that all anodes are connected to single power supply 11. Since the electrolyte only touches the portion of wafer above an anode during the seed layer plating process, the plating current will only pass through the anode and go to that portion of the wafer. The plating process steps are similar to those of Figs. 3A-3B with power supply 11 replacing power supplies 12 and 13.

Figs. 41A-41B show another embodiment of apparatus for plating a conductive film in accordance with the present invention. The embodiment of Figs. 41A-41B is similar to that of Figs. 40A-40B except that the cylindrical walls can move up and down to adjust the flow pattern. As shown in Fig. 41B, cylindrical walls 105 and 107 are moved up, so that the electrolyte flows toward the portion of wafer above walls 105 and 107.

Charge monitors 11A, 12 A, and 13A are used as in-situ thickness monitor. For instance charge variations caused by fluctuation of any power supply can be feed back to a computer. The computer can correct the variation either by adjusting current delivered by the same power supply or adjusting the plating time.

5 An advantage of above process is that no deplating happens during whole plating process. Such deplating would cause additional thickness variation, and might cause corrosion to the plated film.

Figs. 60A-60B show another embodiment of apparatus for plating conductive film in accordance with the present invention. The embodiment of Figs. 60A-60B is
10 similar to that of Figs. 58A-58B except that output of each channel is adapted by multi-small nozzles 800. Those nozzles will enhance the film uniformity.

Fig. 61 shows another embodiment of apparatus for plating conductive film in accordance with the present invention. Plating bath 88 is rotated by a mechanism means (not shown) to form a parabolic surface of electrolyte. Anode 804 is set inside of bath 88
15 and connected to power supply 806. Wafer chuck 29 is driven in x, y, and z movement, and is rotated around the z-axis.

17. Process steps for plating conductive film directly on barrier layer or ultra-thin seed layer.

- 20 Step1: Deliver electrolyte to bath 800;
Step2: Rotate bath 800 around z-axis at a speed of $\omega z2$ to form a parabolic surface on top of electrolyte;
Step 3: Turn on power

anodes. The advantage of these two embodiments is that they provide additional variables to control film uniformity across the wafer.

It should further be apparent to those skilled in the art that various changes in form and details of the invention as shown and described may be made. It is intended
5 that such changes be included within the spirit and scope of the claims appended hereto.

WHAT IS CLAIMED IS:

1. A method for plating a film to a desired thickness on a surface of a substrate, comprising:
 plating the film to the desired thickness on a first portion of the substrate surface;
5 and
 plating the film to the desired thickness on at least a second portion of the substrate surface to give a continuous film at the desired thickness on the substrate.
- 10 2. The method of claim 1 in which the desired thickness is for a continuous seed layer of the film on the substrate.
3. The method of claim 2, further comprising the step of:
 plating an additional thickness on the continuous seed layer to give a continuous film of a second uniform thickness greater than the desired thickness of the seed layer on
15 the substrate.
4. The method of claim 3 in which the film is plated on the first portion of the substrate by flowing an electrolyte on the first portion of the substrate surface and applying a plating current to plate the film on the first portion of the substrate until the
20 film reaches the desired thickness; repeating the electrolyte flowing and plating current flowing steps for at least the second portion of the substrate to plate the film on the second portion to the desired thickness; and flowing electrolyte to the first portion and at least the second portion of the substrate and applying plating current to at least the second portion until the second uniform thickness is obtained.
25
5. The method of claim 4 in which the film is plated on the first and second portions of the substrate by independently providing plating current to plating electrodes for the first and second portions.
- 30 6. The method of claim 5 in which the electrolyte is indepently flowed to the first and second portions of the substrate.
7. The method of claim 1 in which the film is plated on the first and the second portion of the substrate by flowing electrolyte on the first and the second portion of the

substrate at the same time, and applying plating current to plating electrodes for the first and second portions separately.

8. The method of claim 7 additionally comprising the step of providing a
5 sufficient current to the first portion of the substrate to prevent deplating after the film reaches the desired thickness on the first portion of the substrate while applying the plating current to the second portion of the substrate.

9. The method of claim 7 additionally comprising the step of providing a
10 sufficient plating voltage to the second portion of the substrate to prevent deplating while applying the plating current to the first portion of the substrate.

10. The method of claim 7 additionally comprising the step of moving the first
portion of the substrate out of the electrolyte after the film reaches the desired thickness
15 on the first portion of the substrate while applying the plating current to the second portion of substrate.

11. The method of claim 1 in which the film is plated on the first and the second
portion of the substrate by flowing electrolyte on the first portion of the substrate while
20 plating the film on the first portion of the substrate, and by flowing electrolyte to the first and second portion of the substrate at the same time while plating the film on the second portion of the substrate.

12. The method of claim 11 additionally comprising the step of providing a
25 sufficient plating voltage to the first portion of the substrate to prevent deplating after the film reaches the desired thickness on the first portion of the substrate while applying the plating current to the second portion of substrate.

13. The method of claim 1 in which the film is plated on the first and the second
30 portion of the substrate by only flowing electroly

14. The method of claim 1 additionally comprising the step of immersing the substrate surface into electrolyte, and the film is plated in the first and the second portion of the substrate by separately moving a movable jet anode close to the first portion of substrate and moving a movable jet anode close to the second portion of the substrate.

5

15. The method of claim 1 in which the film continues to be plated on the first portion of the substrate while the film is plated on the second portion of the substrate.

16. The method of claim 15 in which the film is plated on the first and the second
10 portion of the substrate by flowing electrolyte on the first portion of the substrate while plating the film on the first portion of the substrate, and by flowing electrolyte to the first and second portions of the substrate at the same time while plating the film on the first and the second portion of the substrate simultaneously.

17. The method of claim 16 in which the film is plated on the first and second
15 portions of the substrate to the desired thickness to give a continuous seed layer, further comprising the step of:
plating an additional thickness on the continuous seed layer to give a continuous film of
a second uniform thickness greater than the desired thickness of the seed layer on the
20 substrate.

18. The method of claim 1 in which the film is plated on the first and the second
portion of the substrate by flowing electrolyte only on the first portion of the substrate
while plating the film on the first portion of the substrate, and by flowing electrolyte to
25 the first and second portion of the substrate at the same time while plating the film on the
second portion of the substrate.

20. The method of claim 19 in which the film is plated on the first and second portions of the substrate to the desired thickness to give a continuous seed layer, further comprising the step of:
plating an additional thickness on the continuous seed layer to give a continuous film of
5 a second uniform thickness greater than the desired thickness of the seed layer on the substrate.

21. The method of claim 1 in which the second portion of substrate is adjacent to the first portion of substrate.

10

22. The method of claim 1 in which the substrate is a semiconductor wafer.

23. The method of claim 22 in which the semiconductor wafer is a silicon wafer.

15 24. The method of claim 23 in which the silicon wafer includes a barrier layer on its top.

25. The method of claim 24 in which the barrier layer is titanium, titanium nitride, tantalum or tantalum nitride.

20

26. The method of claim 24 in which the semiconductor wafer further includes a seed layer on top of the barrier layer.

27. The method of claim 26 in which the seed layer is thicker proximate to a
25 peripheral area and thinner on an inner area of the semiconductor wafer.

28. The method of claim 22 in which the film comprises interconnects in integrated circuits on the semiconductor wafer.

30 29. The method of claim 28 in which the interconnects are in a damascene structure.

30. An apparatus for plating a film on a substrate, comprising:

a substrate holder for positioning the substrate for contact with a plating electrolyte;

at least one anode for supplying plating current to the substrate;

at least two flow controllers connected to supply electrolyte contacting the
5 substrate;

a control system coupled to said at least one anode and said at least two flow controllers to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

10

31. The apparatus of claim 30 in which said at least one anode comprises at least two anodes separated by an insulating wall enclosing each of the at least two anodes.

32. The apparatus of claim 31 in which the insulating wall of each anode is of
15 the same height.

33. The apparatus of claim 31 in which the insulating wall of each anode is of a different height.

20 34. The apparatus of claim 31 in which the insulating wall of each anode proximate to a center of the substrate are higher than the insulating wall of each anode proximate to an edge of said substrate.

38. The apparatus of claim 36 additionally comprising a pressure leak valve coupled to an outlet of the at least one pump.

5 39. The apparatus of claim 36 in which the valves are liquid mass flow control valves.

40. The apparatus of claim 31 in which the at least one control system is configured to selectively supply plating current to said at least two anodes.

10

41. The apparatus of claim 31 additionally comprising a plurality of electrolyte flow channels configured to supply the electrolyte to the successive portions of the substrate.

15 42. The apparatus of claim 41 in which each of said plurality of electrolyte flow channels has an inlet and a plurality of nozzles facing said substrate holder.

43. The apparatus of claim 41 in which two adjacent electrolyte flow channels comprises at least one electrolyte return path between the two adjacent electrolyte flow
20 channels.

44. The apparatus of claim 30 in which said substrate holder is movable up and down for adjusting a gap between said substrate and said anode.

25 45. The apparatus of claim 30 in which said substrate holder is oscillatable in a horizontal direction during plating.

46. The apparatus of claim 30 in which said substrate holder is rotatable around an axis vertical to substrate during the plating process.

30

47. The apparatus of claim 30 further comprising a temperature control device to maintain said electrolyte at a constant temperature during the plating process.

at least one control system coupled to said movable jet anode and said flow controller to provide electrolyte and plating current in combination to successive portions of the substrate to provide a continuous, uniform thickness film on the substrate by successive plating of the film on the portions of the substrate.

5

78. The apparatus of claim 77 in which said substrate holder is rotatable around an axis perpendicular to the substrate.

79. The apparatus of claim 77 in which said substrate holder is movable into the electrolyte to immerse the substrate completely into the electrolyte and movable away from the electrolyte.

80. The apparatus of claim 77 in which said moveable jet anode comprises one anode and an electrolyte flow nozzle enclosing the anode.

15

81. The apparatus of claim 80 in which said movable jet anode further comprises a second electrode outside of and positioned around the nozzle.

82. The apparatus of claim 81 in which said movable jet anode further comprises an insulating wall positioned around the second electrode, and a third electrode positioned around the insulating wall.

20

83. The apparatus of claim 77 in which said movable jet anode is movable in a straight path parallel to the substrate.

25

84. The apparatus of claim 77 in which said movable jet anode is movable in a curved path parallel to the substrate.

85. The apparatus of claim 84 in which the curved path is a spiral path.

30

86. An apparatus for plating a film on a substrate, comprising:
a substrate holder for positioning the substrate in a body of electrolyte;

104. An automated tool for plating a film on a substrate, comprising:
at least two plating baths positioned in a stacked relationship;
at least one substrate holder;
a substrate transferring mechanism;
5 a frame supporting said plating baths, said substrate holder and said substrate transferring mechanism; and
a control system coupled to said substrate transferring mechanism, substrate holder and said plating baths to continuously perform uniform film deposition on a plurality of the substrates.

10

105. The automated tool of claim 104 further comprising:
at least two cleaning modules positioned in a stacked relationship with said at least two plating baths.

15

106. The automated tool of claim 104 in which the substrate transferring mechanism includes a telescoping member movable in x, y and z axes.

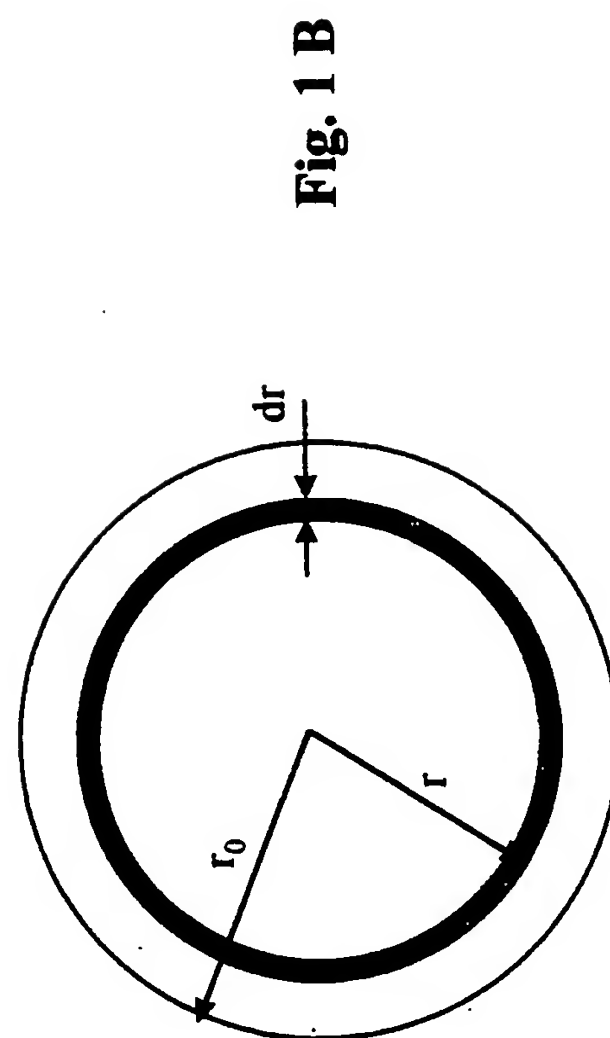
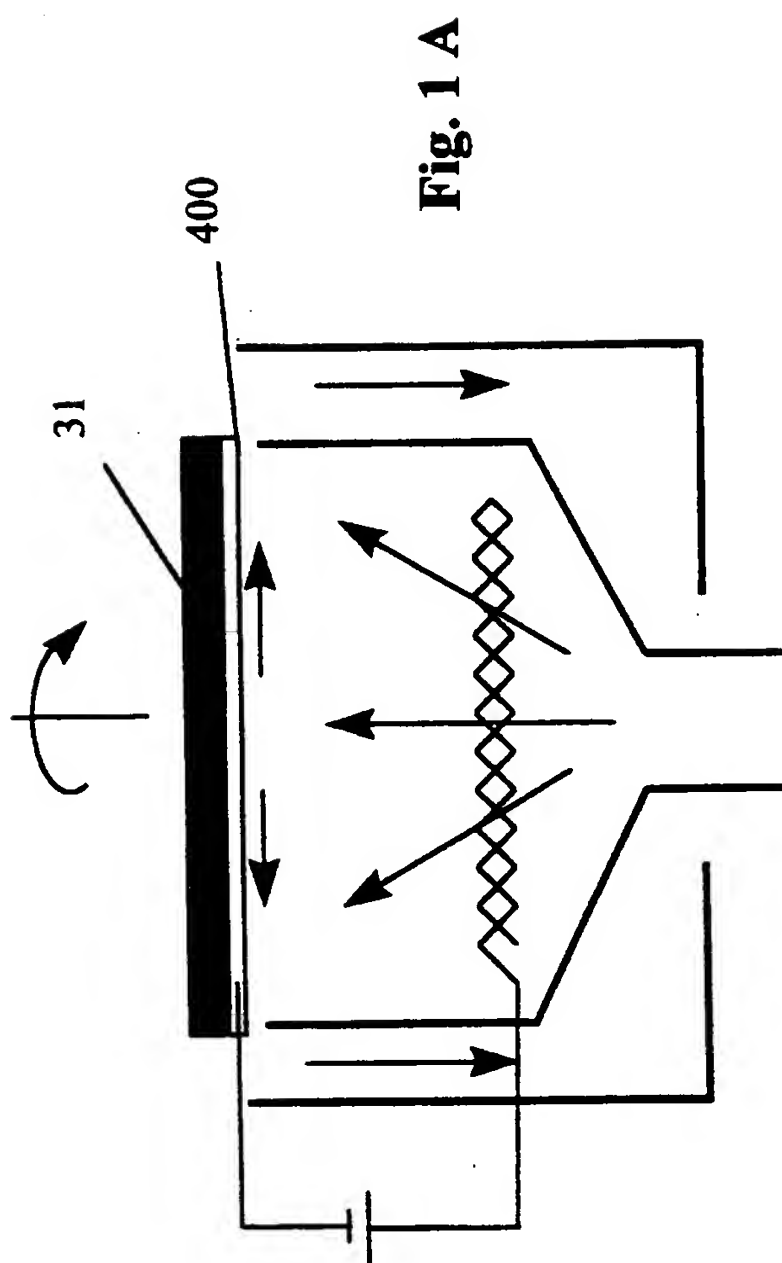
107. The automated tool of claim 104 in which said substrate transferring mechanism is mounted on a bottom portion of said frame.

20

108. The automated tool of claim 104 in which said substrate transferring mechanism is mounted on a top portion of said frame.

109. The automated tool of claim 104 further comprising at least a second set of
25 plating baths positioned in a stacked relationship and at least two additional cleaning modules positioned in a stacked relationship with said second set of plating baths.

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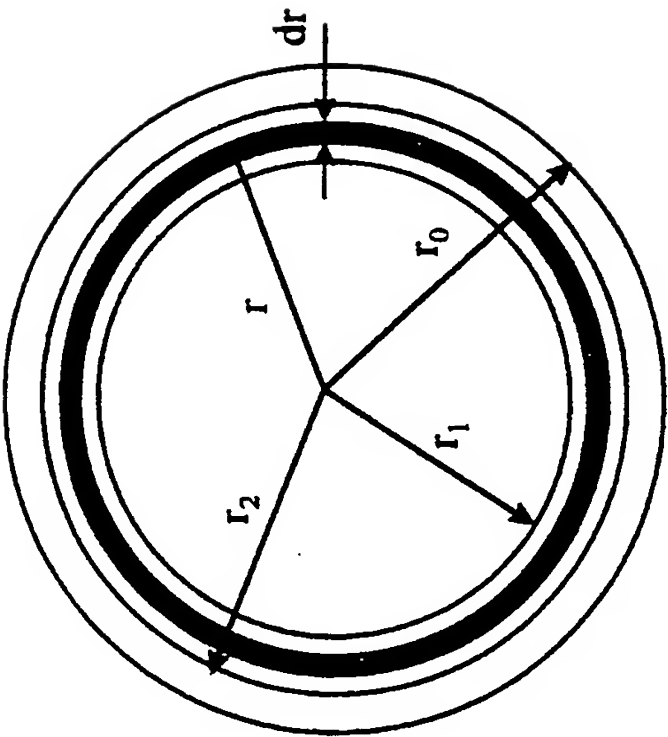


Fig. 2

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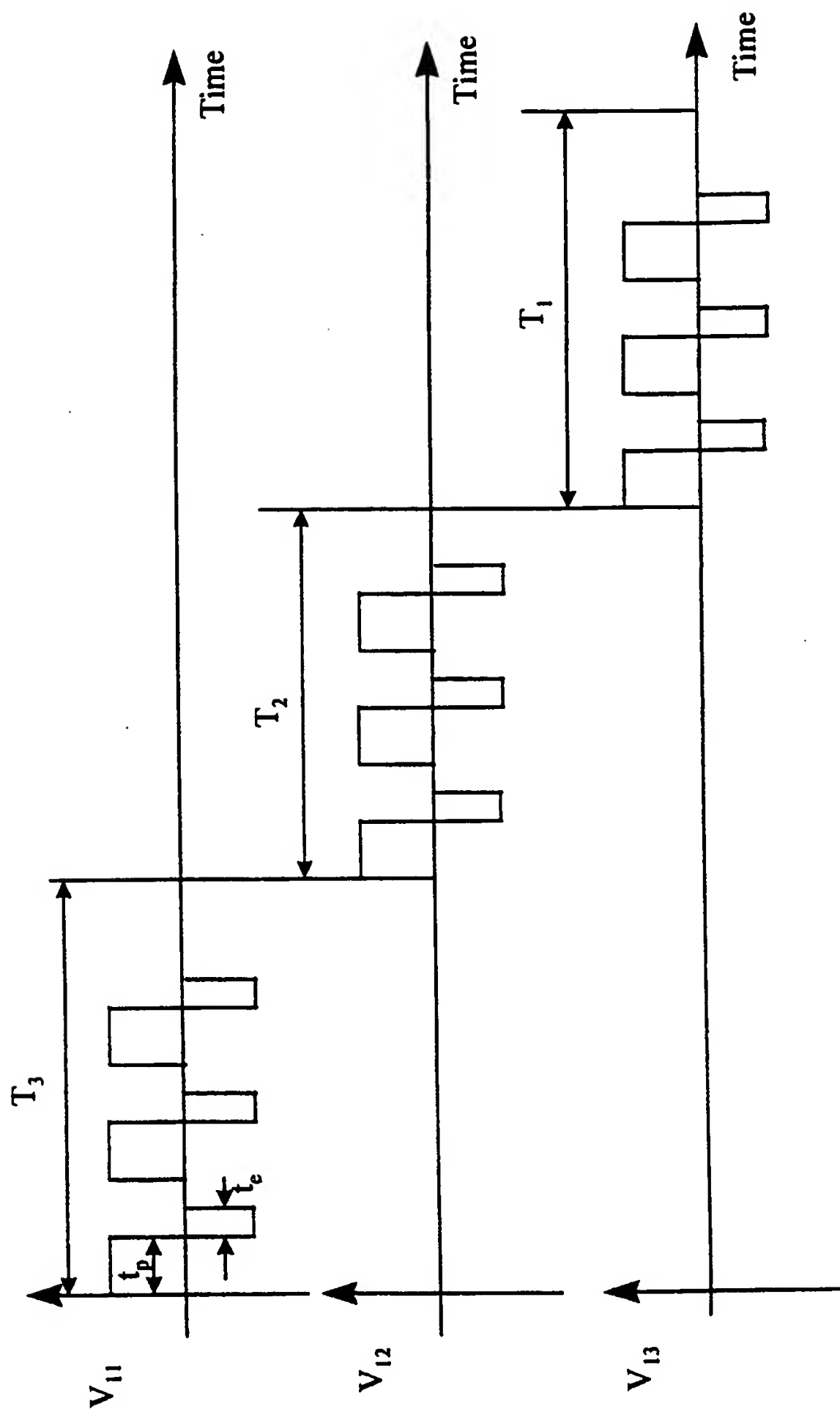


Fig. 5

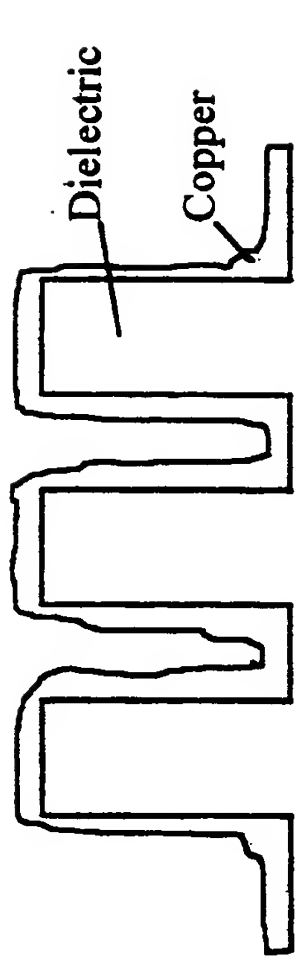


Fig. 6 A Large Ratio of t_e/t_p

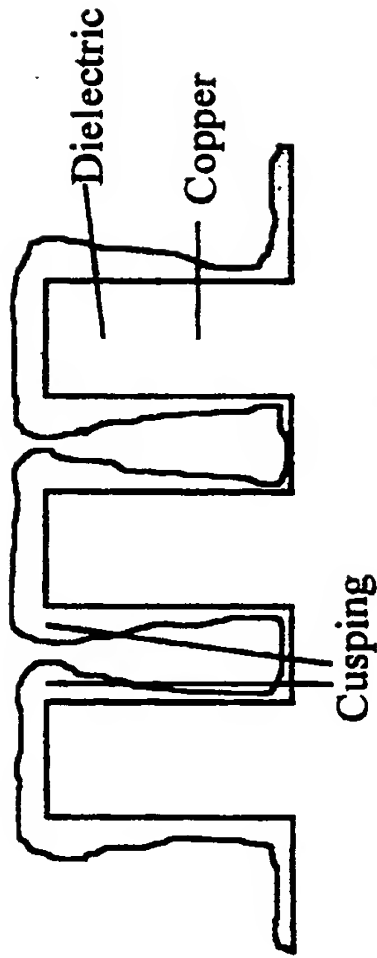


Fig. 6 B Small Ratio of t_e/t_p

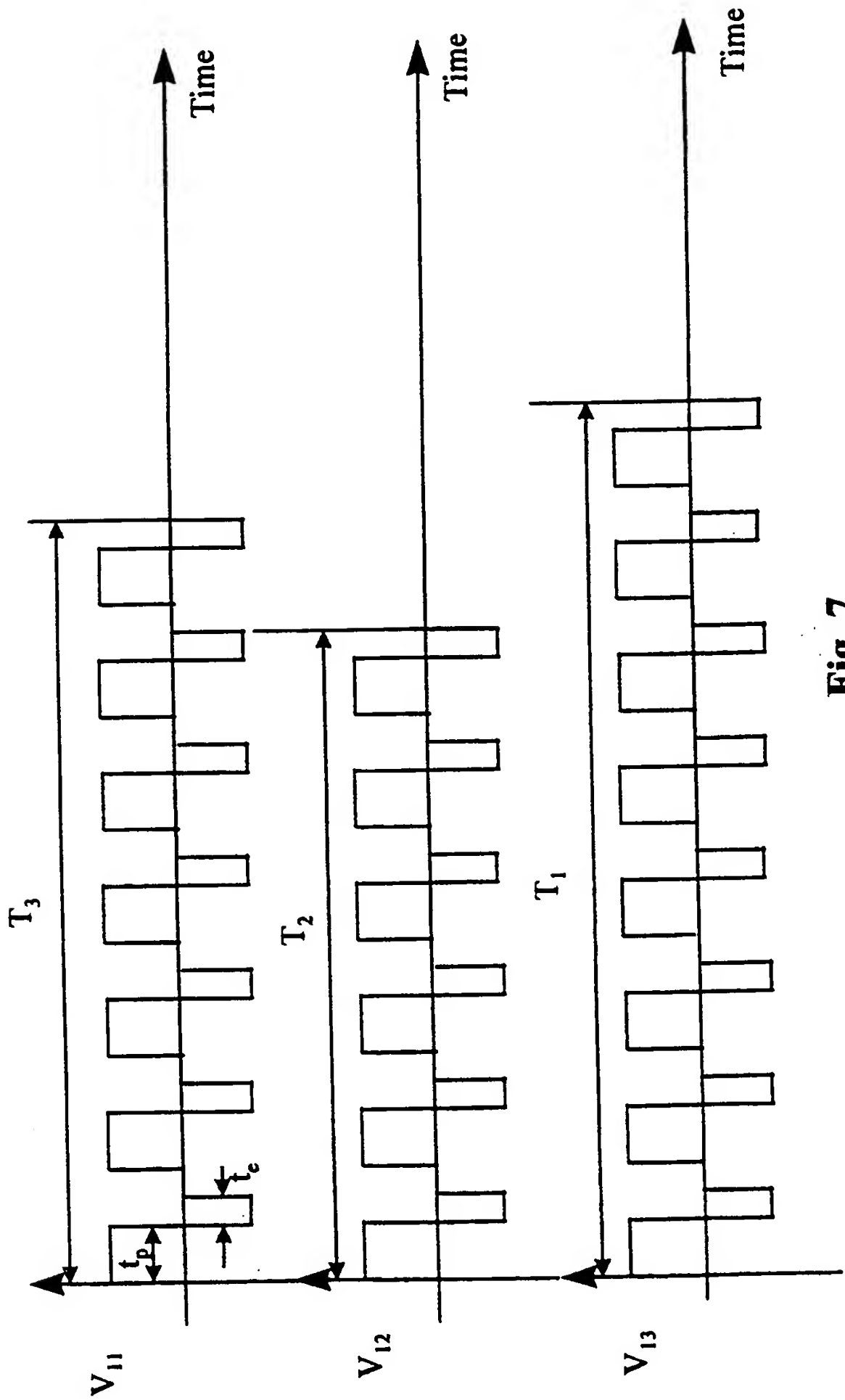


Fig. 7

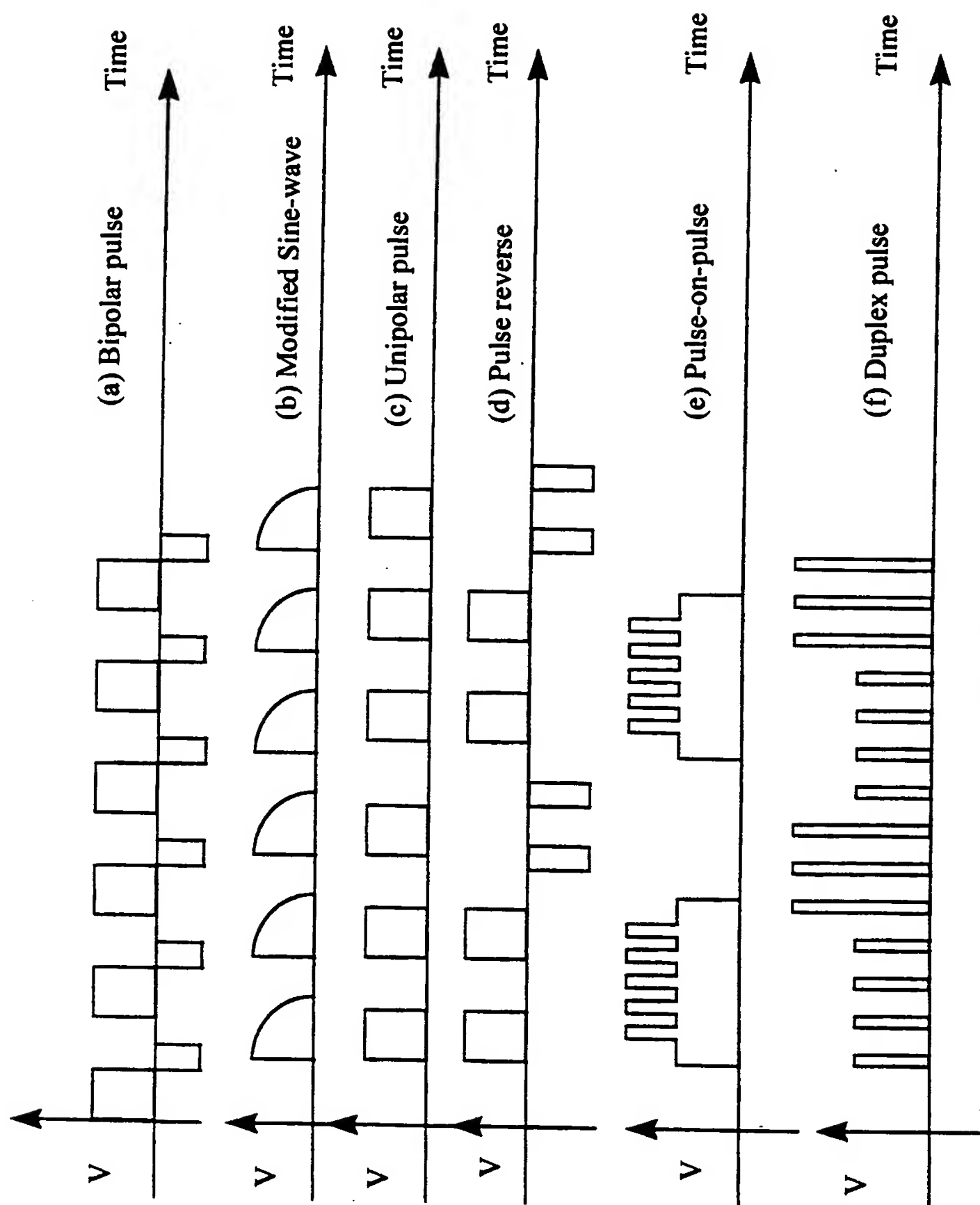


Fig. 8

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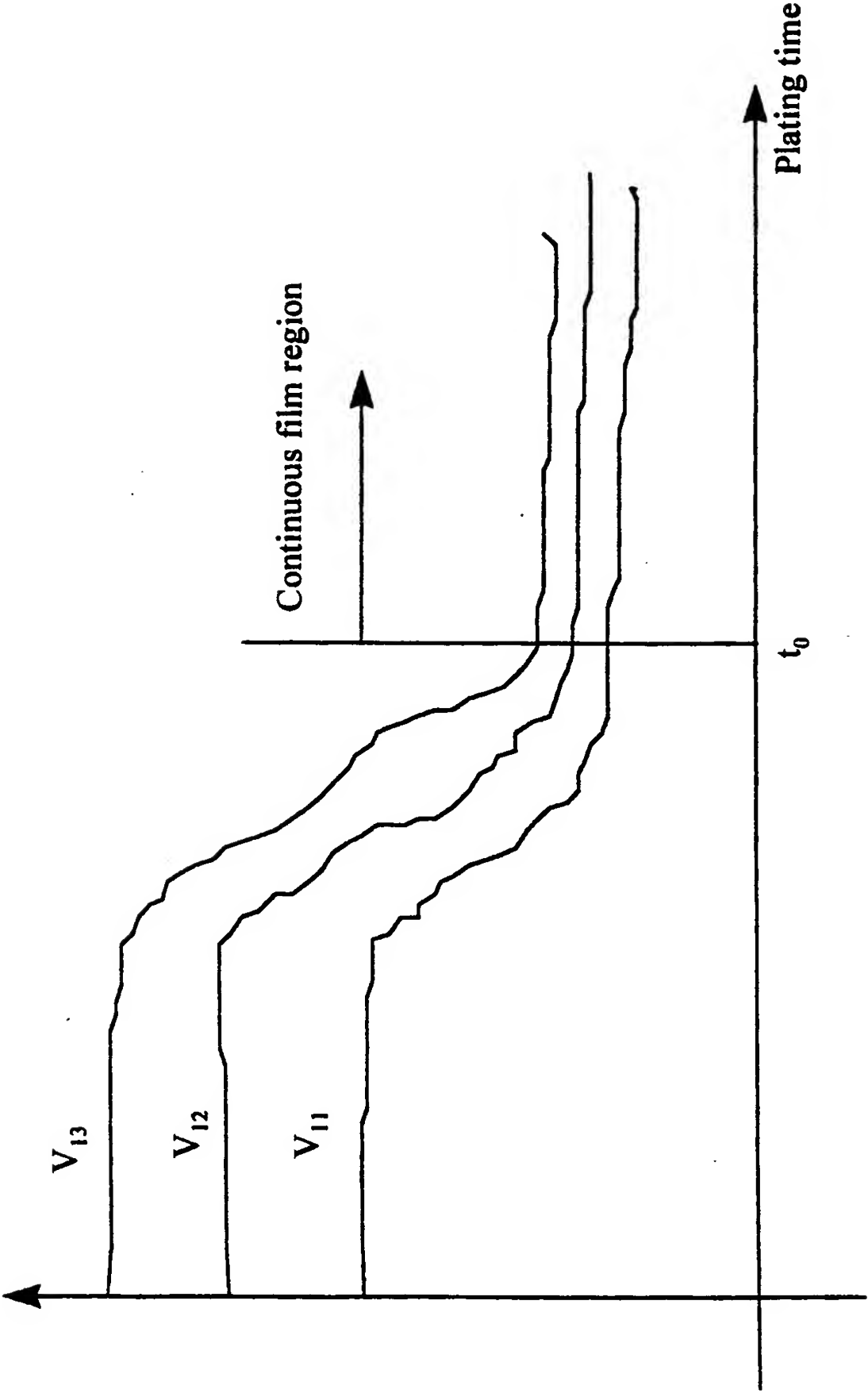
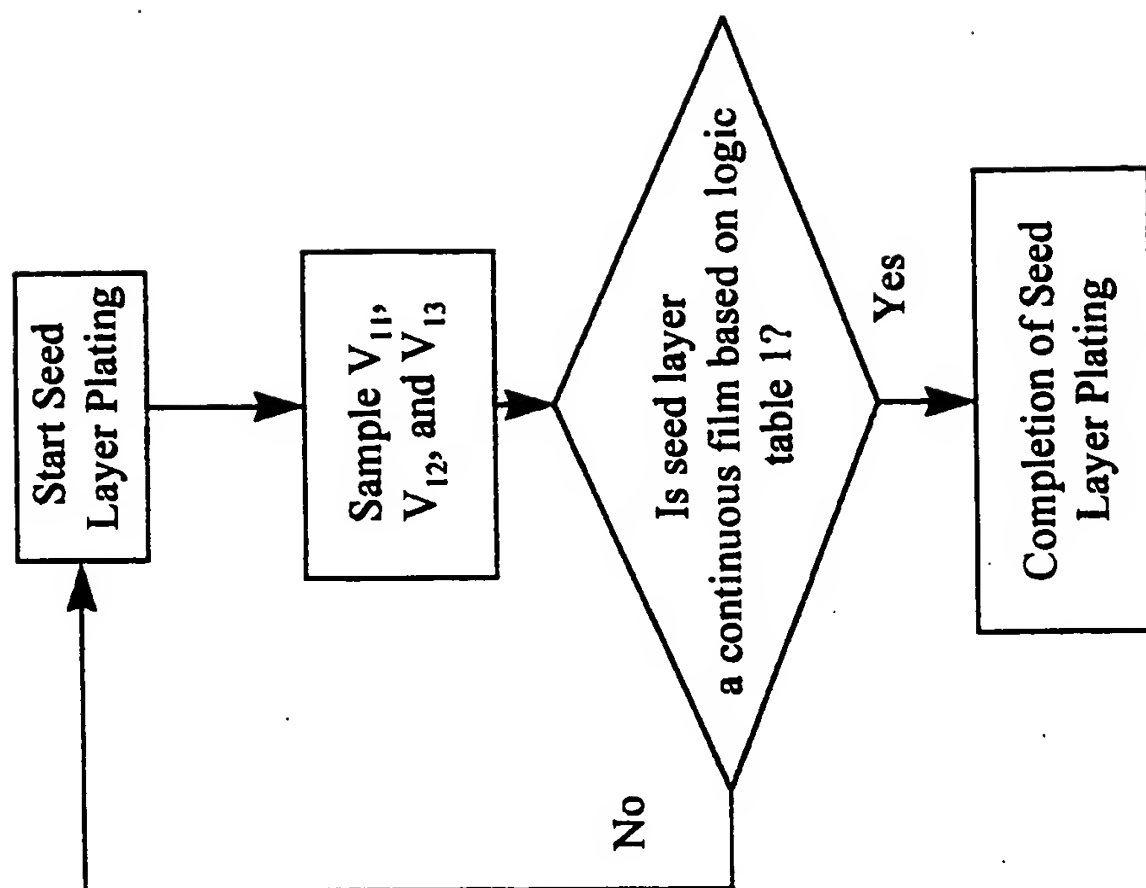


Fig. 10

11/65

**Fig. 11**

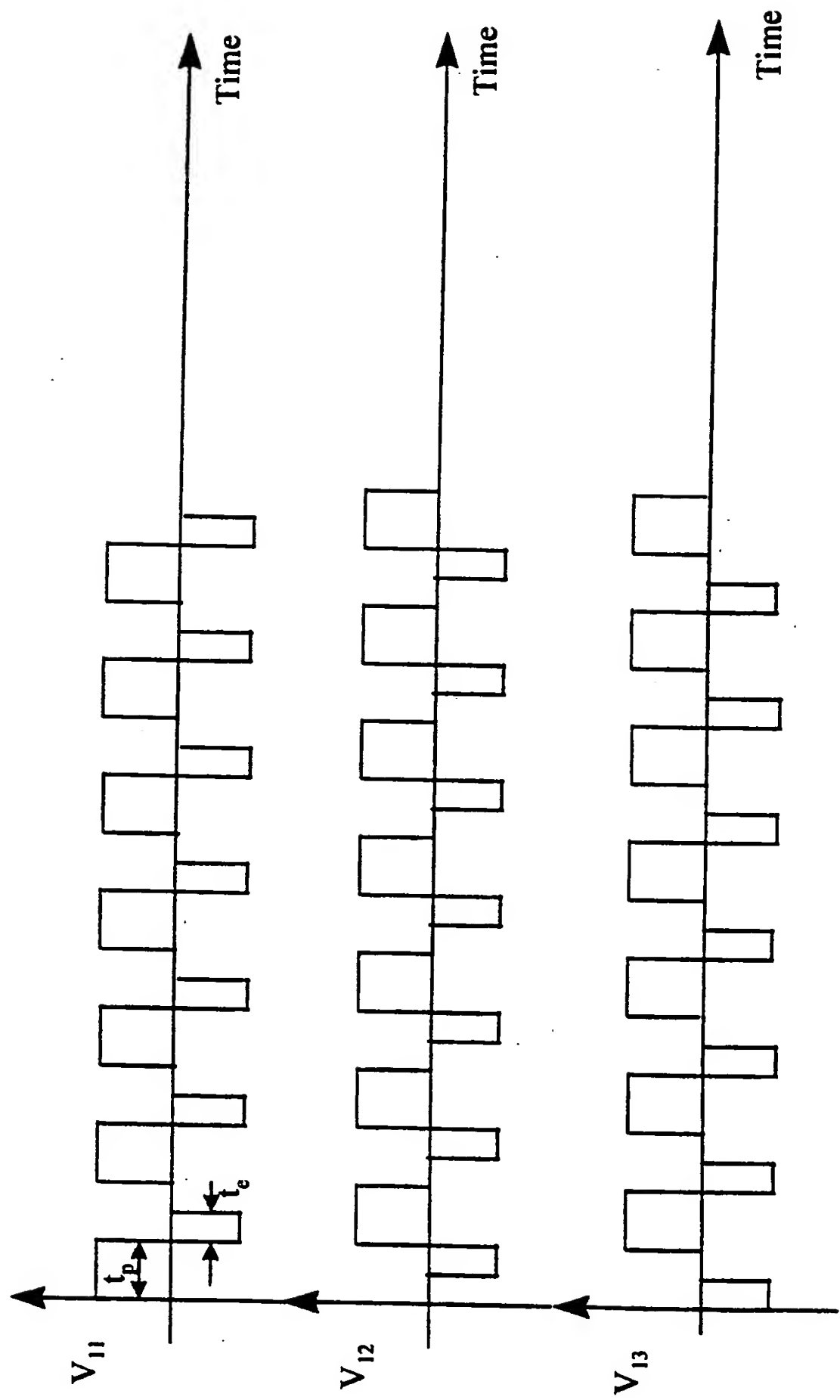


Fig.12

